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2001-085

RESEARCH AND DEVELOPMENT OF AN ADVANCED PERSONAL LOAD CARRIAGE SYSTEM PHASES II AND III

Section B: Analysis of Base Systems Using Standardized Measurement Simulators

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PWGSC Contract No. W7711-5-7273/001/TOS

on behalf of
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October 30, 1997

Analysis of Base Systems
Using Standardized Measurement Simulators

Executive Summary

The overall objectives of this section of the report were: 1) to conduct standardized assessment of five military systems on a computerized Load Carriage (LC) Simulator using a 50th percentile male manikin; 2) to conduct standardized assessments of three of these systems on a Stiffness Simulator; and, 3) to examine the impact of different anthropometric manikins on two base systems. Specifically, the LC Simulator measured variables which assess the load control and load transfer capability of each system whereas the Stiffness Simulator measures the resistance of a pack frame to rotation about three orientations axes. Human responses during First Assessment and Standardized Tests (F.A.S.T.) Trials are reported in Section C and a comparison of these measured dimensions is validated in Section D of this report.

The LC Simulator consisted of interchangeable anthropometrically weighted manikins (50th percentile male used) which were covered with a skin-like surface and driven by computer controlled pneumatic activators programmed to elicit a walking displacement pattern of ±25.4 mm amplitude and 1.4 Hz frequency. A trial consisted of loading the pack to 25 kg (+/- 1 kg) payload, measuring system physical dimensions and properties, mounting the pack, and balancing the moments. Five intervals of 10 seconds of data were recorded over a 1200 second period. By this approach, the pack was assessed on the initial setup and after a sustained period of walking. Output variables were: three dimensional displacement of the pack's centre of gravity relative to the bearer; forces and moments from a three dimensional load cell at the level of the hips; and average contact pressures, peak pressures, and skin forces over the anterior and posterior shoulders, and the upper and lower back.

To examine the resistance of the pack frame to load control motions in three planes, a pack stiffness jig was developed. This jig consisted of a two-piece anatomical human trunk model (50th percentile male) which was designed to limit rotation to one plane at a time. A load cell and a multi-turn precision potentiometer were used to evaluate pack resistance to flexion/extension, torsion, and lateral bending.

None of the load carriage systems were capable of transferring forces to the shoulders without excessive contact pressures, under typical load carriage conditions. System A had high peak reaction forces at the hip level which could lead to discomfort in the lower back. There was also a peak pressure point in the upper back due to a design characteristic of the suspension system. System B had higher hip reaction forces resulting from a higher centre of mass. Standardized tests did not reveal superior suspension or load transfer characteristics. The system clearly favored shoulder loading which was reflected in high contact pressures on the top of the shoulder and low lumbar and sacral pressures. System C was unacceptable as a practical military load carriage system. Excessive pack-torso motion and high reaction moments and amplitudes correlated with poor overall ratings for balance and mobility The pressure on the lower back for this system was excessive at 154 N. This was also reflected in high discomfort scores in extended march tests reported in Section C. System D, as tested, was a working prototype. The suspension and load transfer characteristics observed in standardized tests indicated a stiff suspension with poor pressure distribution at the shoulders, which was typical of System B as well

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1.0 Introduction

1.1 Background

The Defence and Civil Institute of Environmental Medicine (DCIEM) contracted Queen's University to assist in the research and development of an Advanced Personal Load Carriage System (APLCS) in support of the Canadian Forces Soldier Modernization Program, as part of a major crown project D6378 Integrative Protective Clothing and Equipment (IPCE). It is recognized that soldier survival, sustainability, and performance in the field will often require the carriage of significant loads consisting of protective equipment, armaments, and provisions for any future conflict or peacekeeping operations. It is also recognized that soldier survival may depend on carrying moderate or heavy loads over short or long distances. Therefore, the next generation of PLCS should be designed to be compatible with the range of soldier physical, physiological, and biomechanical capabilities for survival, as well as to optimize soldier performance and operational effectiveness. In addition to this next generation project, another major crown project, L2646 Clothe The Soldier (CTS), also has immediate needs for improved PLCS. Both the CTS project, and eventually the IPCE project, require a cost effective and reliable method by which various load carriage equipment designs and components can be tested, evaluated and approved for further military evaluations with representative users in the field.

In the literature reviewed by Knapik et al. (1996), as well as previous reports by Pelot et al. (1995) and Stevenson et al. (1996), it became obvious that physiological measures were valuable for evaluation of a carrier's response to weight, terrain, climatic conditions, and load carrying duration (Haisman, 1988; Gordon et al., 1992; Holewijn, 1989; Morrisey, 1988; Sagiv et al., 1994). Variables relating to psychophysical responses or performance measures are often better correlated to specific load conditions or pack features (Balogun et al., 1986; Goslin & Rorke, 1986; Haisman, 1988; Karmon et al. 1996; Holewijn, 1990; Kirk & Schneider, 1992; Robertson et al., 1982).

Anatomical and biomechanical measures have been used less frequently but appear better able to discern differences in load location and impact of altering pack design characteristics. For example, load location has been studied both physiologically and biomechanically. The physiological approach was sensitive to front-back vs back only carrying strategies (Legg & Mahanty, 1985). Kinoshita (1985) found differences in walking as a result of load location using film analysis and Bobet & Norman (1982) used electromyography to observe differences in muscular effort required. Holewijn and Lotens (1992) used performance-based measures and found that a vertically centred load placement was more acceptable than either a higher or lower load location. Postural changes were also considered a problem, especially if a pack required greater than 15° of forward lean (Bobet & Norman, 1982; Holewijn 1990; Kinoshita, 1985). Knapik et al. (1992) reported that 6% of soldiers (n=335) had injuries during a march, 22% of which were related to low back strains and pains. Balogun et al. (1986) reported that soldiers were apt to incur blisters due to friction and bruising on the iliac crests of the pelvic bones. This is indicative of poor or inappropriate load transfer to the body.

Other biomechanical studies have been focused on the measuremnt of balance or load control variables. Kram (1991) conducted a study where loads were balanced on the ends of bamboo poles, and found that ground reactions forces were less, probably due to energy transfer between the poles and the person. This method of load carriage is not acceptable to soldiers but, if the energy transfer capabilities could be recreated in a LC suspension system, then metabolic costs could be reduced. Experienced trekkers prefer packs with maximum adjustability so that site of load transfer can be varied from the shoulders to the hips as physical and thermal comfort requires (Morton, 1994). This is especially important with the advent of larger volume backpacks (Parker, 1990).

Background literature reviews and focus group work with soldiers has lead to the conclusion that two main areas of interest when investigating load carriage are load control and load transfer. Proper load control is necessary for the user to maintain balance and mobility during load carriage. Relative displacement between user and load carriage system, rotational moments generated during load carriage, and resistance of the LC system to deflections within the range of human motion, are measures which can be used to define the load control ability of a load carriage system. Capacity for load carriage, muscle fatigue during carriage, and risk of tissue injury are all dependent on load transfer to the user. Measurement of skin contact pressures, specifically in significant load bearing

areas, and forces applied by the load allows for an increased understanding of load transfer in LC systems.

Typical LC systems are still comprised of two shoulder straps and a hip belt which are joined to form a suspension system for the load. A pack or rucksack is attached to this suspension system to carry the load. It is the suspension system that is responsible for load transfer to the person. However, load weight and load distribution characteristics within the pack/ruck are the main determinants for load control. It is hypothesized that load transfer will affect a person's comfort, which will be a result of factors such a skin pressures, and joint reaction forces. It is also hypothesized that load control is more related to factors such as pack-person relative displacements, pack stiffness and joint reaction moments.

1.2 Objectives

This contract, a continuation of an earlier DCIEM contract #W7711-47225/01-XSE, had the overall objectives of developing improved design assessment tools and to use these tools in development of a valid and reliable comprehensive measurement system for military load carriage. These objectives are discussed, with results, in Sections A - F and the Executive Summary of this report. The specific objectives of this report section were:

1. To compare and rank seven (7) marching order systems on the LC simulator with the 50th percentile male mannikin. Due to equipment availability, four (4) complete systems were tested in marching order. (Scope 7f).
2. To determine the effects of wearing a fragmentation vest with marching and battle order. Base systems were compared with the fragmentation vest (Scope 7a6).
3. To compare and rank the top three (3) marching order systems across the different mannikin sizes. In agreement with the Interim Report (March, 1997), only two (2) systems were investigated across different anthropometric mannikins. (Scope 7a4, 7f-2).
4. To compare and rank seven (7) systems in terms of pack stiffness about the principle axes of rotation. Because of logistics only three (3) systems were tested completely. (Scope 7g).

1.3 Summary of Load Carriage Systems Tested

Table 1.1 provides an overview of the LC system combinations which were tested on the LC Simulator. The Australian (A) and the British (B) were tested with their own webbing systems. The Canadian 1982 Pattern Rucksack and the DACME Packboard Rucksack were tested with both the current issue webbing and the in-service load carriage vest on the simulator.

Table 1.1 Codes used to describe the Marching Order test configurations for LC Sim Tests

BASE SYSTEMS for L.C. Sim Tests	MARCHING ORDER			
	Pack and Webbing		Pack and LCV	
	No Frag	+Frag	No Frag	+ Frag
Australian (A)	ANF[1, 2]			
British (B)	BNF[1, 2]			
Canadian '82 (C)	CWNF[1]	CWF[1, 2]	CVNF	CVF[1, 2]
DACME (D)	DWNF[1]	DWF[1]	DVNF[1]	DVF[1]

[1] Systems tested for torsional stiffness.
[2] Systems tested for flexion and lateral bending stiffness.

1.4 Summary of Load Carriage Measurements

Testing on the Load Carriage Simulator (LC Sim) for the base systems was performed by the Ergonomics Research Group at Queen's University, and included measurement of the following variables:

1. Shoulder strap and waist belt tension.
2. Relative displacement between LC system and torso.
3. Hip reaction forces.
4. Hip reaction moments.
5. Skin contact pressures in five regions.

Testing on the LC Compliance Tester for the base systems was performed by the Clinical Mechanics Group at Queen's University, and included measurement of the following variables:

1. Torsional pack stiffness over the range from 0 to 12° rotation.
2. Lateral pack stiffness over the range from 0 to 35°.
3. Flexion/extenstion stiffness over the range from 0 to 48° forward bending.

2.0 Methods

2.1 LC Simulator

A Load Carriage Simulator was constructed under Phase 1 of this project (Contract # W7711-4-7225/01-XSE, 1995) with improvements developed through the current contract. These improvements included an improved control system, the addition of a six degree of freedom load cell to measure ground reaction forces and moments, mannikins representing the 5th, 50th percentile females and 50th and 95th percentile males and improvements to the strap sensors and pressure measurements systems. For marching orders, packs were loaded with approximately 25 kg with webbing or load carriage vests containing an additional 10 kg of ammunition, water, and kit. The LC Simulator is shown in Figure 2.1-1.

Figure 2.1-1. LC Simulator, with mannikin.

The typical protocol for marching order on the Load Carriage Simulator involved tightening the pack straps to field test conditions (using strap force gauges), leaning the mannikin forward to create a zero moment (balanced position), and collecting ten stride cycles at 10, 300, 600, 900 and 1200 second intervals. A detailed protocol is available in Annex A.1. The outcome measures, reported in Figure 2.1-2, were standardized across conditions and consisted of:

1. **Relative Motion between Pack and Person**

   These data were recorded using a three dimensional electromagnetic device. Outcome variables consisted of relative motion between the pack and person in the X direction (pack moving closer/away from the body), Y direction (medial/lateral motions) or Z direction (up/down motions).

2. **Skin Contact Pressures**

   A Tekscan™ Pressure sensor system was used to acquire contact pressure data over the shoulder, upper and lower back and hip areas. Pressure data were taken at four primary sites: 1) top and front of the shoulder, 2) back along the line of the scapula, 3) lower lumbar and upper sacral area, 4) lower sacral and buttocks area. Contact pressure data were reported in terms of magnitudes and distribution.

   A) **Magnitude of Pressures**
      - average values (kPa)
      - peak values (kPa)
      - pressure distribution index (PDI), peak to average ratio (hot spot)

   B) **Distribution of Pressures**
      - peak values (kPa)
      - generalized map of pressure distribution

3. Force and Moments of Force

Ground reaction forces and moment data were taken using a 6 degree of freedom load cell (AMTI MC5-6-10000) based on a fixed body axis system at the hip and along the long axis of the trunk. The outcome variables were:

A) Ground Reaction Forces

These forces are indicative of the ground reaction force a person must provide at the level of the hip to counter balance any eccentric forces. The force values were reported as average maximum/minimum and mean values in:

- F_x (forward and back)
- F_y (side to side)
- F_z (up and down)

B) Reaction Moments

Moment calculations were also used in the analysis to identify the magnitude of the counter-balancing moments that needed to be created by muscles above the hips to offset the moments created by the forcing function of the Load Carriage Simulator. Moment values were recorded as average range (maximum - minimum) and mean values for:

- M_x (side to side moments)
- M_y (forward/back moments)
- M_z reflecting torsional moments.

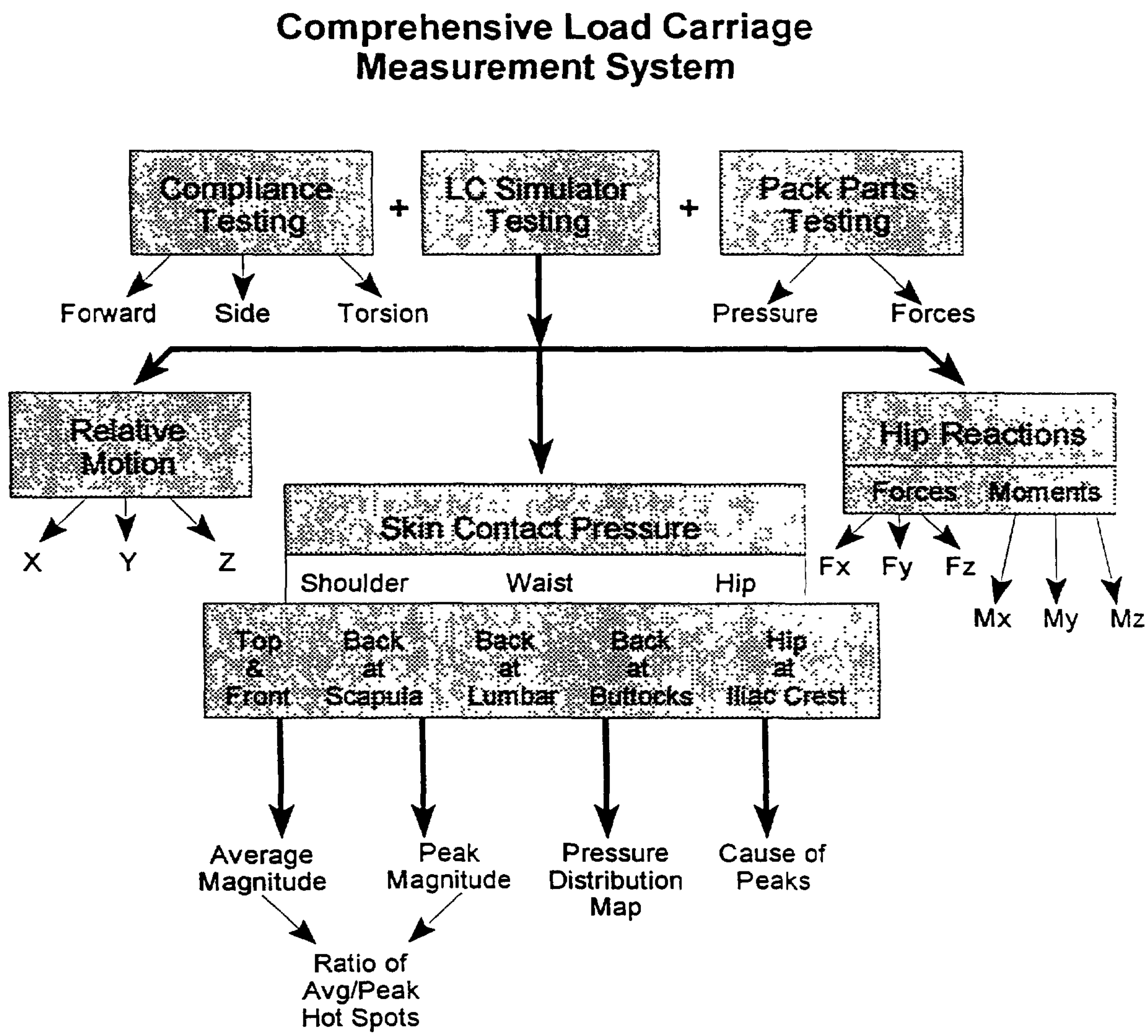


Figure 2.1-2. Diagram of output variables from LC Simulator and Stiffness Testing Jig.

2.1.1 Torso Specifications and Preparation

A family of four anthropometric mannikins (5^{th} and 50^{th} percentile females, and 50^{th} and 95^{th} percentile males, as defined by Safework™ anthropometric software) were constructed for LC simulator testing. Each mannikin was comprised of a head and trunk section, with arms truncated in the mid-humeral region and legs extending to just below the buttocks.

These human models consisted of a fibreglass outer shell with an expandable poured polyurethane foam filling. Proper mass distribution was achieved by thoroughly mixing aggregate with the interior foam. A vertical cylindrical cavity was created in each mannikin to allow for mounting of a 6 degree-of-freedom load cell. In each case, the neutral axis of the load cell was positioned at the approximate location of the centre of rotation of the mannikin's hips. This load cell was further mounted on a single axis articulating vice, which permitted the mannikin and LC system to be placed in a balanced anterior body lean position for load carriage. Finally, the surface of each mannikin was covered with a 5 mm thickness of Bocklite™, a synthetic skin-like material used on prosthetics, to approximate the compressive response of human skin over bone. For all tests, the mannikin was dressed in a Canadian Forces standard issue combat shirt.

2.1.2 LC System Loading and Mass Properties

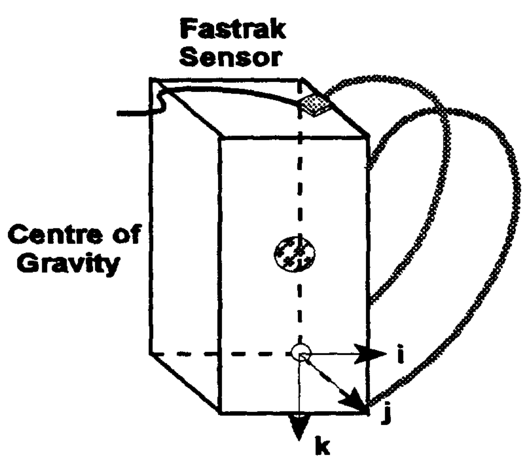
LC payload was created by locating a block of mass at the centre of the system volume. The mass used in the LC system was 25 kg +/- 1 kg and was comprised of rectangular steel plates. These plates were held in position by a rigid polystyrene foam shell which filled the LC volume. Three dimensional location of the LC system centre of gravity and LC system moments of inertia about the three pack axes are available in Table 2.1 for the pack with payload. The mass of the loaded pack is also included.

Table 2.1-1 Mass properties of load carriage systems. Total mass for the loaded LC system, location of the centre of gravity in three dimensions, and the physical dimensions of the LC system are all included.

Mass Properties of Load Carriage System	A System	B System	C System	D System	E System
Mass (kg):					
LC System w/load	27.1	26.2	27.6	26.3	0
Physical Size (mm):					
Length (k)	-520	-450	-630	-600	-540
Width (j)	340	320	370	370	340
Depth (i)	-170	-180	-300	-300	-300
Centre of Gravity (mm):					
Length (k)	-320	-260	-390	-380	*
Width (j)	155	174	155	200	*
Depth (i)	-139	-126	-90	*	*

*Data not recorded

Note: i) Physical size and C of G measurements are relative to the lower left corner of the LCS as it is worn.
ii) Frame on System E broke during human trials and was not tested on the LC Sim.



2.1.3 Test Protocol

The LC Simulator (Figure 2.1-3) consists of the previously described rigid mannikin, mounted on a programmable displacement platform. This platform rests on three air cylinders which allow vertical motion as well as rotation about the x (anterior/posterior) and y (medial/lateral) axes. A computer controlled vertical displacement pattern (+/- 25.4 mm amplitude, 1.8 Hz frequency) simulated marching, and linear displacement transducers provided positional information for the control system. Feedback control was accomplished by varying the differential pressure across each cylinder face.

The duration of one LC System test was 1200 seconds, with data recorded at 10 seconds (initial data set), and at each 300 second interval. Sampling rate for all data collection was 55 Hz and the duration was 10 seconds (minimum). The outcome measures from the LC system tests consisted of the relative displacement between mannikin and load carriage system, skin contact pressures on the shoulders, upper back, and lower back, and hip reaction forces and moments. The following sections describe the methodology and instrumentation used to collect LC System characteristic data.

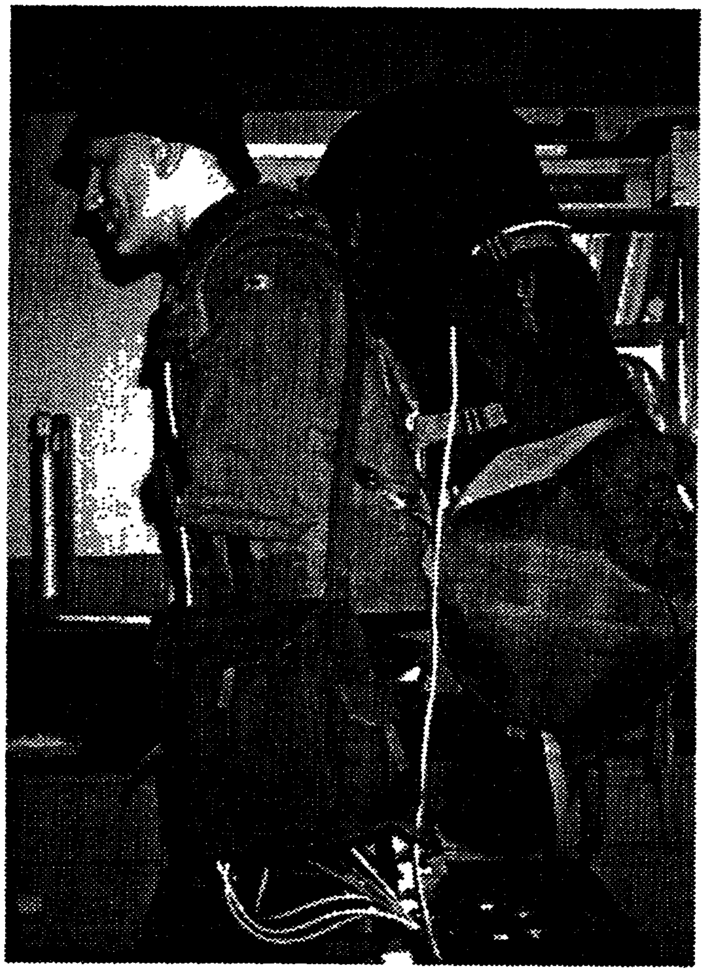


Figure 2.1-3. LCS C positioned on LC Simulator mannikin.

2.1.4 Strap Forces

The force transducers were constructed with four foil style strain gauges, attached in a full Wheatstone bridge configuration to a rounded I-shaped 6061-T6 aluminum carrier with a length of 38.00 mm and thickness of 1.14 mm. Static testing of the transducers showed they were highly linear (r^2>0.9995) with a small standard error (<0.01 V).

During the setup phase of the LC Simulator testing, strap force tension transducers were placed in-line in the right lower shoulder strap and the right half of the waist belt, free of any hip/kidney padding. Attachment of the transducers was accomplished by placing a pin through an attachment ring in the end of the carrier material of each transducer, ensuring that all tension in the strap was transmitted through the transducer. Output from the force transducers was received and amplified by a Keithley MetraByte DATAQ system (Keithley MetraByte Instruments Incorporated). Initial settings of 55 +/- 5 N in the shoulder strap and 40 +/- 5 N in the waist strap were used for all load carriage trials. The mean tension for the lower right shoulder strap and the right waist belt for each test of each base system are presented in Table 2.1-2. The full data set for one trial is included in Annex B.1.

Table 2.1-2. Shoulder strap and waist belt tension for the Base Systems. The mean tension in these two suspension elements, along with the standard deviation, is presented.

	Tension (N)	SD (N)
Shoulder Strap	55	5
Waist Belt	40	4

2.1.5 Relative Displacement of LC System and Torso

An electromagnetic position tracking system (Fastrak™ by Polhemus Incorporated) was used to provide three dimensional displacement data. The source for the Fastrak™ was affixed with nylon screws to the underside of the left arm of the mannikin. A Fastrak™ sensor was also attached in a secure position to the superior polystyrene surface of the LC System payload. Displacement data, for the payload with respect to the source, was recorded for 10 seconds at 55 Hz at 300 second intervals over the duration of the test. Translation from the superior payload sensor location to the loaded pack centre of gravity was performed to estimate resultant displacement vectors between the centre of gravity of the loaded LC system and the mannikin. Relative displacements were averaged over the the duration of the test and reflect the peak to peak motion (range). This data is reported in terms of a total relative displacement (mm), in which the range of displacement in the X (forward and back), Y (side to side), and Z (up and down) directions were combined vectorially using the following equation:

$$Displacement_{total} = \sqrt{X_{range}^2 + Y_{range}^2 + Z_{range}^2}$$

Increased displacement of the LC system, with respect to the solider, can cause decreased agility due to reduced load control. Unrestrained displacement of marching order kit and LC equipment also leads to stability problems and local discomfort due to repeated collisions between the solider and items.

Direct comparison of Fastrak™ positional data with data collected from an opto-electric positional recording system (Optotrak™ by Northern Digital Incorporated) with high precision (RMS error <0.01 mm) provided an RMS error for Fastrak™ data of 0.65 mm.

2.1.6 Reaction Forces and Moments

Ground reaction forces and moments were collected using a 6 degree-of-freedom load cell (AMTI Incorporated, MC5-6-10000) based on a body fixed coordinate system located at the hip and oriented along the long axis of the trunk. The outcomes from this instrumentation were reported as a resultant total force (N), in which reaction forces in the F_x (forward and back), F_y (side to side), and F_z (up and down) were combined vectorially using the following equation:

$$F_{total}=\sqrt{F_x^2+F_y^2+F_z^2}$$

Similarly, a resultant total moment (Nm) was defined in which the moments M_x, M_y, and M_z were components. The convention for describing moments references the axis about which that moment acts, therefore M_x acts about the x axis and corresponds to a side to side torque, M_y acts about the y axis and corresponds to a forward - backward torque, and M_z acts about the z axis. Two factors affect the moments and forces transmitted through the load cell: motion and mass of the moving bodies. In the LC simulator, the mass of the torso requires a significant force from the positioning actuators to track the imposed displacement. This is in addition to the reactions needed to move the payload itself. To compensate for these effects, a two-step procedure is used. First an initial run of the 50th percentile mannikin with no load carriage system in place is used to generate a baseline of reaction moments and forces. These values are then subtracted from the results of a run in which a load carriage system is being evaluated.

The second step is to normalize the reaction values by dividing them by the total weight of the system. The total weight is the sum of the load in the pack, the weight of the pack itself, and the weight of additional load carriage devices (such as webbing or fragmentation vests).

The resultant *normalized* values are expressed as Nm/kg for moments and N/kg for forces. This method of normalization is typical for biomechanical measurements. A normalized force of 9.81 N/kg indicates a force of 9.81 Newtons acts for each kilogram of load carried. This is equivalent to the weight of the complete load carriage system configuration and is sometimes expressed "1 x Payload Weight". A normalized force of 12.2 N/kg, for example, would be expressed as 12.2/9.81 = 1.24 x Payload Weight..

Reaction forces represent the force which a person must provide at the hip to counter balance any off center forces resulting from the load carriage system and contents. Similarly, the net reaction moments reflect the magnitude of counter balancing torque that the muscles at the hip must provide to offset any moments created during normal gait, or by the forcing function of the simulator. In both cases, the greater the muscle force needed to maintain balance, the greater the soldier fatigue, both locally and overall, leading to discomfort and pain.

2.1.7 Skin Contact Pressures

The F-Scan™ pressure sensing system (Tekscan Incorporated) was used to acquire contact pressure data on the mannikin skin over the anterior shoulder and posterior scapula areas, as well as in the low back region. Figure 2.1-4 shows the orientation of the F-Scan™ 9810 pressure sensors, which were affixed to the mannikin with a non-permanent spray adhesive. The F-Scan™ system uses a matrix of force sensitive resistors, which are arranged in a rectangular pattern and contained between two flexible polyester plastic sheets. At full size there are 96 force sensitive resistors, spaced over a region 206 mm by 76 mm. When the thin polymer foil in an element is compressed, the voltage passed across the element changes. This change is sensed by system software, and is recorded as a load normal to the sensor surface, based on individual calibration for each sensor. Information is transferred to the computer through a signal processing unit and cable to a computer card. This information can be replayed in 'movie' format, which can give a dynamic measurement of force, average and peak pressures, active area, or duration of contact. Previous testing at Queen's (DCIEM Contract #W7711-4-7225/01-XSE) has found the F-Scan™ system standard error of the mean to be 9.6 % for average pressures and 14 % for peak pressures. Also, use of the sensors on a curved surface leads to a 9% standard error of the mean for average pressure results.

For LC system testing, pressure data were reported in terms of peak dynamic pressures (kPa) and average pressure (kPa) over all active cells of the sensors in the anatomical areas of interest: anterior shoulder; posterior shoulder (scapula); hip; and lower back. Research has shown that blood occlusion can occur when tissues are continuously loaded at an average pressure of 14 kPa for 8 hours. Average skin contact pressures of 20 kPa have also been associated with discomfort in 95 % of a test sample.

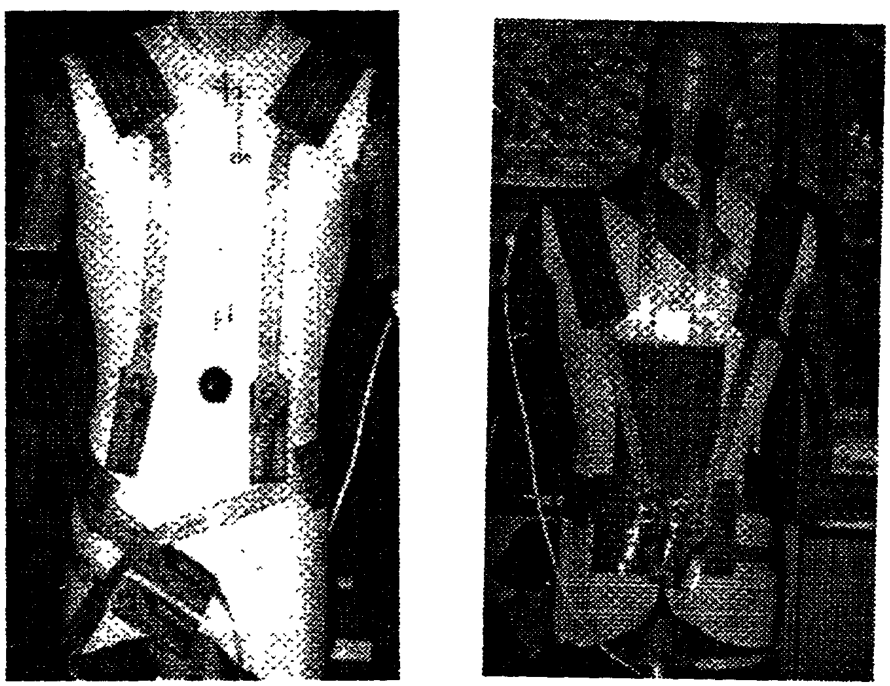


Figure 2.1-4. LC Simulator mannikin, with F-Scan™ pressure sensors in place.

2.2 Load Carriage (LC) Compliance Tester

2.2.1 Torso Specification and Preparation

A three degree of freedom compliance tester which allows the placement of each load carriage system onto a two-piece anatomical human trunk model (50th percentile male) was developed. The model was custom-fitted with a layer of compliant synthetic skin, 5mm thick Bocklite™. The upper torso portion of the model was free to rotate about a horizontal axis (y-axis for forward bending or x-axis for sideways bending) on two oil impregnated metal powder sintered bearings at the L3/L4 location of the human spine, or about the vertical axis (z-axis for torsional twisting) on a thrust bearing at the L4/L5 location. Only one degree of freedom was active for each type of test, with the other degrees of freedom mechanically locked. The lower waist portion of the model was fixed in an upright position to the steel support frame. The LC Compliance Tester is shown in Figure 2.2-1. Please note that numerically, the stiffness of a material is equivalent to the inverse of its compliance.

2.2.2 Test Protocol

Empty load carriage systems were used in this test to generate baseline LC system stiffness values, without the increased pack stiffness due to kit items. Each pack was placed in position on the model and all straps were securely fastened. Using in-line force transducers, the shoulder straps and the hip/waist strap were pre-tensioned to 55 N and 40 N respectively, the same settings were used in the load carriage simulator tests.

During each test run, analog signals from the two load cells and two potentiometers were captured using a data acquisition system (Keithley MetraByte Instruments Incorporated) in a portable personal computer at a sampling rate of 5Hz over a three minute period. A spreadsheet was used to post-process the data, where each data set was partitioned into the first cycle and repeated cycles. Only the loading phase of each test cycle was analyzed. Load cell data was filtered first by averaging over one or two degree intervals of rotation and further averaged over two to four repeated test runs . For the forward and sideways bending tests, the torso displayed an apparent resistance against the bending motions. Baseline reference tests were established for the compliance

tester using the upper torso without pack or clothing and a baseline correction was applied to the data sets by subtraction. For the torsional stiffness tests, upper torso response had an insignificant effect on the torque transducer output and the baseline correction was not applied. The information was reduced to bending moments or torque about the hinge in Nm and relative rotation in degrees to produce characteristic moment-rotation curves for each pack configuration. Linear regressions were performed on each LC system data set to obtain an aggregate pack stiffness (slope of the linear regression).

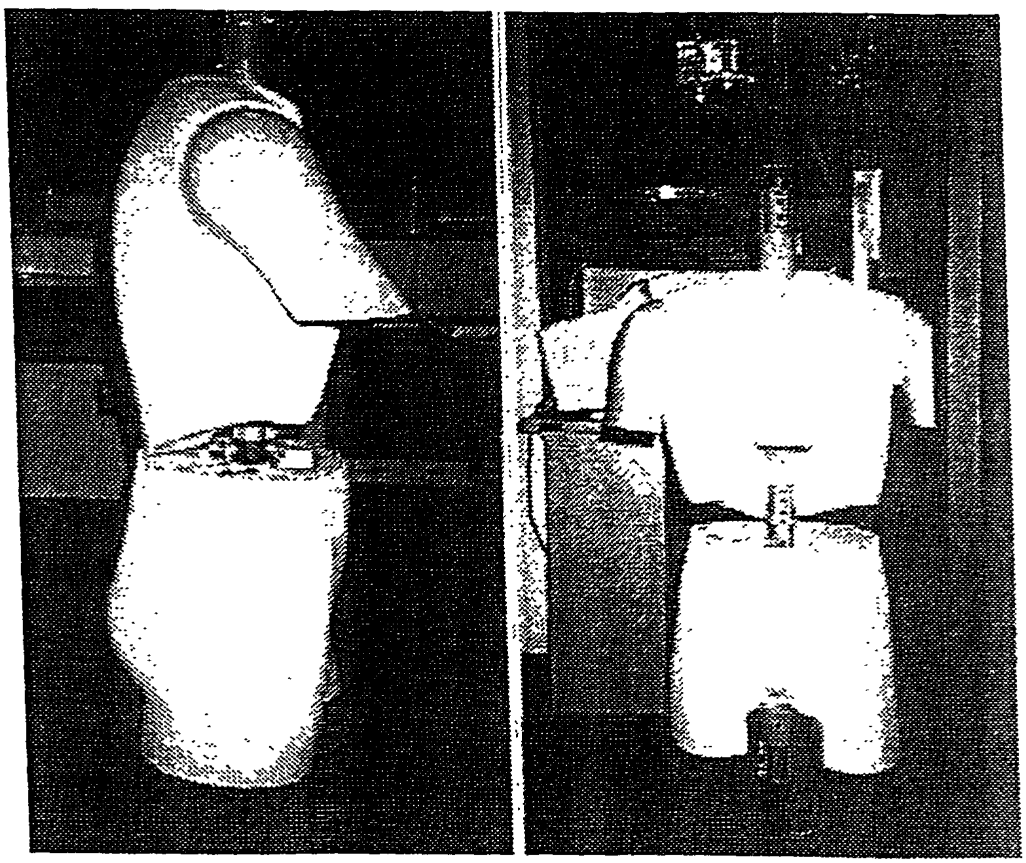


Figure 2.2-1. LC Compliance Tester.

2 2.3 Torsional Stiffness

For the torsional stiffness tests, torque was applied in the form of a measured horizontal force acting on a moment arm of 0.137m. This was achieved by means of a cable wrapped around a 0.273m diameter pulley on the upper torso support.A winch (Fulton Performance Products Incorporated) fitted with a multi-turn precision potentiometer (Bourns Electronics) was used to generate and measure rotation of the upper torso relative to the waist section of the trunk. A strain gauged torsion load cell was installed on the drive shaft to measure pack resistance to such rotations. Studies have shown that the average relative angle of twist during walking is approximately 18 degrees full scale which is ±9 degrees about the neutral axis. A value of 12 degrees from neutral was used as the maximum for testing. Load was applied manually with the winch in a 60 second test cycle (25s ramp up, 10s hold, 15s ramp down, and 10s hold) in order to minimize inertial loads from the trunk model. Each test included three test cycles before adjustments were made to the setup (straighten clothing, tighten straps, position pack) and testing was repeated to ensure reproducibility.

2.2.4 Lateral Bending Stiffness

A moment was applied in the form of a horizontal force acting on a moment arm of 0.927m. This was achieved by means of two opposing cables attached to the load transfer assembly (LTA) on a roller track. Each cable was pre-tensioned by a 5 kg mass to maintain alignment. An in-line tension transducer, similar to those used in the measurement of strap forces during LC simulator testing, was installed between the loading cable and the LTA to measure cable tension changes. A second winch fitted with a potentiometer was used to induce and measure the horizontal displacement of the LTA. For the lateral bending tests, the anatomical trunk model was rotated 90 degrees vertically about the base while keeping the hinge bearing assembly in its original orientation with respect to the LTA. The excursion of the LTA was reduced to a maximum of 0.305m, resulting in a maximum sideways bending angle of 18 degrees. The normal range expected during walking/marching gait is about 2-7 degrees.

2.2.5 Forward Bending Stiffness

For the forward bending tests, load was applied in the form of a forward force acting on a moment arm of 0.927m. The maximum excursion of the LTA was 1.035 m resulting in a 48° forward bending angle. In the forward bending test, the upper torso displayed an apparent resistance to motion. Baseline reference tests were established for the LC Compliance Tester (upper torso without pack, equipment or clothing). Load was applied manually with in a 60 second test cycle (25s ramp up, 10s hold, 15s ramp down, and 10 s hold) in order to minimize inertial loads from the trunk. Each test included three test cycles before adjustments were made to the setup (straighten clothing, tighten straps, position pack) and testing was repeated to ensure reproducibility. Linear regressions were performed on each data set to obtain an aggregate pack stiffness (slope of the linear regression) and the initial pack resistance (intercept of the linear regression).

3.0 Results of Base Systems Analyses

3.1 LC Simulator - Relative Displacements

Table 3.1 is a summary of relative payload motion between pack and person. Due to a fracture of the pack frame base system ENF was not available for simulator testing but was part of human trials (Section C).

The three external frame systems: ANF, CWNF, and DWNF, all had greater pack motion in the forward/backward (x) direction, with system C exceeding 13 mm. In the side to side (y) direction CWNF had twice the motion of other base systems with all packs being comparable in the up/down (z) direction. Only System C exceeded the total displacement value of 12 mm recommended in an earlier report (Stevenson et al., 1995) where it had been proven that there was a loss of agility under dynamic conditions with increased pack-person motion.

Table 3.1 Relative Motion of Payload - Base Systems

Displacement (mm)	ANF	BNF	CWNF	DWNF
x	5.4	2.7	13.6	4.6
y	2.7	3.2	6.3	2.9
z	10.5	11.1	11.4	9.2
Total	**12.1**	**11.9**	**18.8**	**10.5**

3.2 LC Simulator - Reaction Moments and Forces

3.2.1 Reaction Moments

Table 3.2-1 represents the mean reaction moments and the normalized (to LCS load) mean reaction values respectively. The mean reaction values give an estimate of the total counter moment that must be generated by muscles when walking with that LCS. Load masses varied slightly between trials, normalized means allow comparison across packs and different payload conditions. Based on Table 3.2-1 it is necessary for the soldier to use greater muscular effort to counter balance the moments of the CWNF pack in comparison to the other base systems. The total hip moment is 56.4Nm, with larger values in all directions, indicating that this design requires larger muscular effort to maintain balance and control even under the controlled condition of level walking.

Table 3.2-1. Mean and Normalized Mean Reaction Moments - Base Systems

Reaction Moments	**ANF**	**BNF**	**CWNF**	**DWNF**
Means (N.m)				
Mx	15.8	16	20.2	15.1
My	41.1	43.6	52.1	41.4
Mz	4.9	3.2	7.4	3.4
Total	**44.3**	**46.6**	**56.4**	**44.2**
Normalized Mean(N.m/kg)				
Mx	0.03	0.06	0.03	0.05
My	0.36	0.32	0.03	0.32
Mz	0.06	0.09	0.03	0.11
Total	**0.37**	**0.34**	**0.05**	**0.34**

3.2.2 Reaction Forces

Mean and normalized mean reaction forces at the hip represent the force which a person must provide at the hip joint to counter balance any off-center forces resulting from the person, load carriage system and contents. The greater the force values, the greater the muscular effort needed to maintain balance or to overcome when tasks of mobility are required. Table 3.2-2 has the data for this comparison. All systems were comparable in this regard with 249 N of reaction force required in the forward/backward direction because of the body lean and 574.8 N to 617.6 N in the upward direction to carry the vertical load due to the pack and upper body weight. However, when normalized to payload, ANF had the largest forward (x) force and smallest side to side (y) component which could lead to better mobility but perhaps back discomfort due to the need to counter balance forward shear forces.

Table 3.2-2 Mean and Normalized Mean Reaction Forces - Base Systems

Reaction Forces	**ANF**	**BNF**	**CWNF**	**DWNF**
Means (N)				
Fx	282	259.4	24937574.8	29742608.3
Fy	37.6	41.4		
Fz	580.8	617.6		
Total	**646.7**	**671.1**	**627.5**	**678.2**
Normalized Means (N/kg)				
Fx	10.03	9.09	5.78	9.34
Fy	-1.52	-1.36	-1.30	-1.19
Fz	8.85	8.88	8.87	8.93
Total	**13.46**	**12.78**	**10.67**	**12.99**

3.2.3 Amplitudes of Reaction Moments

Table 3.2-3 represents the mean amplitude and normalized (to LCS weight) mean amplitude for hip joint reaction moments. These amplitudes are created because of the sinusoidal oscillations of the simulator's that mimics the vertical displacement of the body's centre of gravity during walking. These values are the amplitude of the counter balancing moments needed by the muscles at the hip. This would be indicative of the magnitude of the cyclic muscle contractions needed to counter off-centre forces during gait.

CWNS had the largest mean value (112.7 Nm) and normalized mean value (0.78) of all four packs, indicative of the fact that there was a larger energy cost inherent in this design which would increase the risk of muscule fatigue. The amplitude of the forward moment (My) indicates what range of counter balancing forces would be needed at the hips.

Table 3.2-3 Amplitude of Reaction Moments - Base Systems

Moment Amplitude	**ANF**	**BNF**	**CWNF**	**DWNF**
Means (Nm)				
Mx	31.5	32.1	40.3	30.2
My	82.1	87.1	104.2	82.9
Mz	9.7	6.4	14.7	6.9
Total	**88.5**	**93**	**112.7**	**88.5**
Normalized Means Nm/kg				
Mx	0.12	0.12	0.06	0.04
My	0.23	0.29	0.78	0.22
Mz	0.11	0.04	0.06	0.04
Total	**0.28**	**0.32**	**0.78**	**0.23**

3.2.4 Amplitudes of Reaction Forces

Table 3.2-4 represents the average amplitude and normalized amplitude for joint reaction forces. BNF was high in both the Fx and Fz directions resulting in a total hip reaction force amplitude of 731.8 N. This was also reflected in the normalized amplitude especially for the Fz. The short length of the BNF system and the fact that it is a shoulder carried system results in a higher overall center of gravity for the user. This system requires less forward lean to balance it which results in a greater Fz force on the hip. This configuration has been shown to provide improved load control and balance (Stevenson et al., 1995).

Table 3.2-4 Amplitude and Normalized Amplitude of Reaction Forces - Base Systems

Reaction Force Amplitude	ANF	BNF	CWNF	DWNF
Means (N)				
Fx	364.7	396.1	397.6	425.4
Fy	56.1	65.6	81.4	53.3
Fz	519.7	611.9	505.7	535.4
Total	**637.3**	**731.8**	**648.4**	**685.9**
Normalized Means (N/kg)				
Fx	3.35	3.32	-0.19	3.81
Fy	0.00	0.15	0.06	-0.07
Fz	7.32	9.84	4.54	6.82
Total	**8.05**	**10.39**	**4.54**	**7.81**

3.3 LC Simulator - Pressure Measurements

Pressure measurements were made with the F Scan ™ from sensors placed over the anatomical locations outlined in the sub section 2.1.7 of this report. Test results from these measurements, for all base systems, can be found in Tables 3.3-1 to 3.3-4. The tables consist of the *average pressure* for one recording of 10 seconds during the 600 second sample as well as the *peak pressure* experienced during this sample and the *ratio of peak pressure to average pressure* (pressure distribution index or PDI) and the *body force* experience by the wearer as a result of pressure in these areas. The data on contact pressures is presented in tabular form for mean numeric values and in pictorial form for location of the peak pressure.

3.3.1 Contact Pressure on the Left Front & Top Shoulder - Base Systems

The pressure sensor was oriented so that pressures on the front and top of the shoulder underlying the shoulder strap could be evaluated (See Figure 2.1-2). The BNF system exceeded all other systems in terms of average pressure and peak pressure at 31.2 kPa and 92.7 kPa respectively. This was a result of the system being totally shoulder supported with no effective waist belt. DWNF had a 88.5 kPa peak pressure underlying a buckle and a relatively high body force of 115.7N. ANF and CWNF were comparable in the shoulder area across all variables. When results were compared to recommended design guidelines all systems exceeded the average recommended pressure of 14kPa with no system exceeding the peak pressures of 120kPa based on the Stevenson et al., (1995) report which recommended that shoulder joint reaction forces not exceed 135N and that the body forces not exceed 50N. The biomechanical model was not used in this study to compare shoulder joint reaction forces, however, all but the CWNF pack exceeded the recommended shoulder body force value of 50N. These large pressures and forces predispose the top and front of the shoulder to muscular fatigue.

Table 3.3-1. Contact Pressure on Left Shoulder, Front and Top - Base Systems.

Pressure Measures	ANF	BNF	CWNF	DWNF
Average	23.5	31.2	20.5	24.2
Peak (kPa)	42.2	92.7	47.4	88.5
PDI (kPa)	1.8	3.0	2.3	3.7
Body Force (N)	70	132	35.7	115.7

3.3.2 Contact Pressure on Left Scapula - Base Systems

An F-Scan sensor was positioned to capture the pressures and forces on the back of the shoulder and upper back over the area of the shoulder blade. Table 3.3-2 provides numeric data from this testing.

The average pressures for the left scapula varied from 16.4 kPa to 24.1 kPa for all systems thus not meeting the recommended design limit of 14 kPa. The peak pressure on the left scapula for the ANF system was highest at 61.7 kPa, a value below the recommended design limit. BNF and DWNF had a better pressure distribution index (PDI) which would indicate a smoother application of force across the shoulder strap but the same two systems had the highest body force application across the back of the shoulder. When comparing these results to the front of the shoulder, Systems B and D had their peak values near the top of the shoulder suggesting that the total shoulder pressure was larger for these systems. This indicates that systems B and D would be more prone to excessive shoulder fatigue that system A.

Table 3.3-2. Contact Pressure on Left Scapula - Base Systems.

Pressure Measures	ANF	BNF	CWNF	DWNF
Average (kPa)	19.9	17.8	24.1	16.4
Peak (kPa)	61.7	44.9	73.8	34.7
PDI (kPa)	3.1	2.5	3.1	2.1
Body Force (N)	49.8	81.9	73.9	99.2

3.3.3 Contact Pressures at Lumbar Spine - Base Systems

Table 3.3 -3 contains pressure values, for all base systems, measured in the lumbar area where the upper part of the waist belt and lumbar pad is situated. Both the ANF and CWNF systems are within the recommended average pressure design limit of 14 kPa whereas BNF and DWNF are not. The BNF system places greater body force than the other systems at 42.2N on the lumbar spine but none of these peak values exceed the recommended design limit of 120N. Although system CWNF had the largest PDI value, the magnitude of the peak pressure is relatively low and the contact area small, resulting in little body force against the lumbar spine. This was because it is a long frame which does rest on this area. The concentration of pressures in the lumbar area for Systems B and D suggests that the soldier would be prone to fatigue and strain at this location.

Table 3.3-3. Contact Pressure at Lower Lumbar / Top of Sacrum - Base Systems.

Pressure Measures	ANF	BNF	CWNF	DWNF
Average (kPa)	13.2	34.9	8.5	41.6
Peak (kPa)	23.8	81.9	22.1	81.9
PDI	1.8	2.3	2.6	2.0
Body Force (N)	25.6	42.2	4.1	10.1

3.3.4 Contact Pressure at Sacrum/Buttocks - Base Systems

Table 3.3-4 contains all contact pressure data for base systems, as measured in the area of the mannikin's sacrum and buttocks. The ANF system was very balanced in its application of load across the upper and lower back and within recommended design limits. The BNF system pressures were reduced in this area because it is a shorter pack mainly and does not extend to this distance. However, the CWNF system had a tenfold increase in average pressure with body forces at 154.8N, a value six times greater than its counter parts. This would suggest that the CWNF would cause a muscular fatigue problem or pressure point problems in the lower back around the sacral lumbar junction and is likely to cause discomfort.

Table 3.4-4. Contact Pressure at Sacrum / Buttocks - Base Systems.

Pressure (kPa)	**ANF**	**BNF**	**CWNF**	**DWNF**
Average	16.7	30.2	76.6	22.9
Peak	38.4	50.2	235.0	50.2
PDI	2.3	1.7	3.1	2.2
Body Force (N)	25.6	24.5	154.8	28.2

3.4 LC Compliance Testing - Test Results of Base Systems

The LC compliance tester allows motion about one axis at a time in three planes of motion. Stiffness testing of the Base Systems was performed about three axes: torsional motion was induced about the Z (superior/inferior) axis; lateral bending was induced about the X (anterior/posterior) axis; and flexion-extension was induced about the Y (transverse) axis. Table 3.4-1 provides a summary of LC system stiffness. Most of the research on stiffness was conducted to compare the impact of fragmentation vests and load carriage vests and is discussed in Section 6.0.

Figures 3.4-1 to 3.4-3 represent the types of outputs found during repeated test cycles. There is typically an initial low level stiffness value from 0 to 3 degrees of rotation corresponding to tensioning the loading cable in the absence of cable pretension. No baseline adjustments were necessary in the torsional tests. However, in forward and sideways bending tasks, there was a characteristic baseline response due to the effects of gravity and geometry on the test jig. This response was measured and subtracted from pack test results. The forward and lateral bending baseline offsets are presented in Figures 3.4-2 and 3.4-3 respectively. The net moment response curves were either linear or bilinear in nature indicating that the packs were stiffer initially and then resistance changed with increased lean until belt or strap slippage occurred. The first and repeated cycles were different but reproducible for all loads carriage systems tested.

System A had the highest torsional stiffness and forward bending stiffness. BNF had a high lateral bending stiffness of 4.1 Nm/degree but this is somewhat misleading as the waist belt sits high on the torso and interfered with the bending mechanism.

Table 3.4-1. Base System Stiffness Values.

System	System Stiffness (Nm/degree of rotation) Torsional Bending	Lateral Bending	Forward Bending
ANF	2.6	0.6	0.4
BNF	0.3	4.1	0.2
CWNF	1.0	-	-
DWNF	2.0	-	-

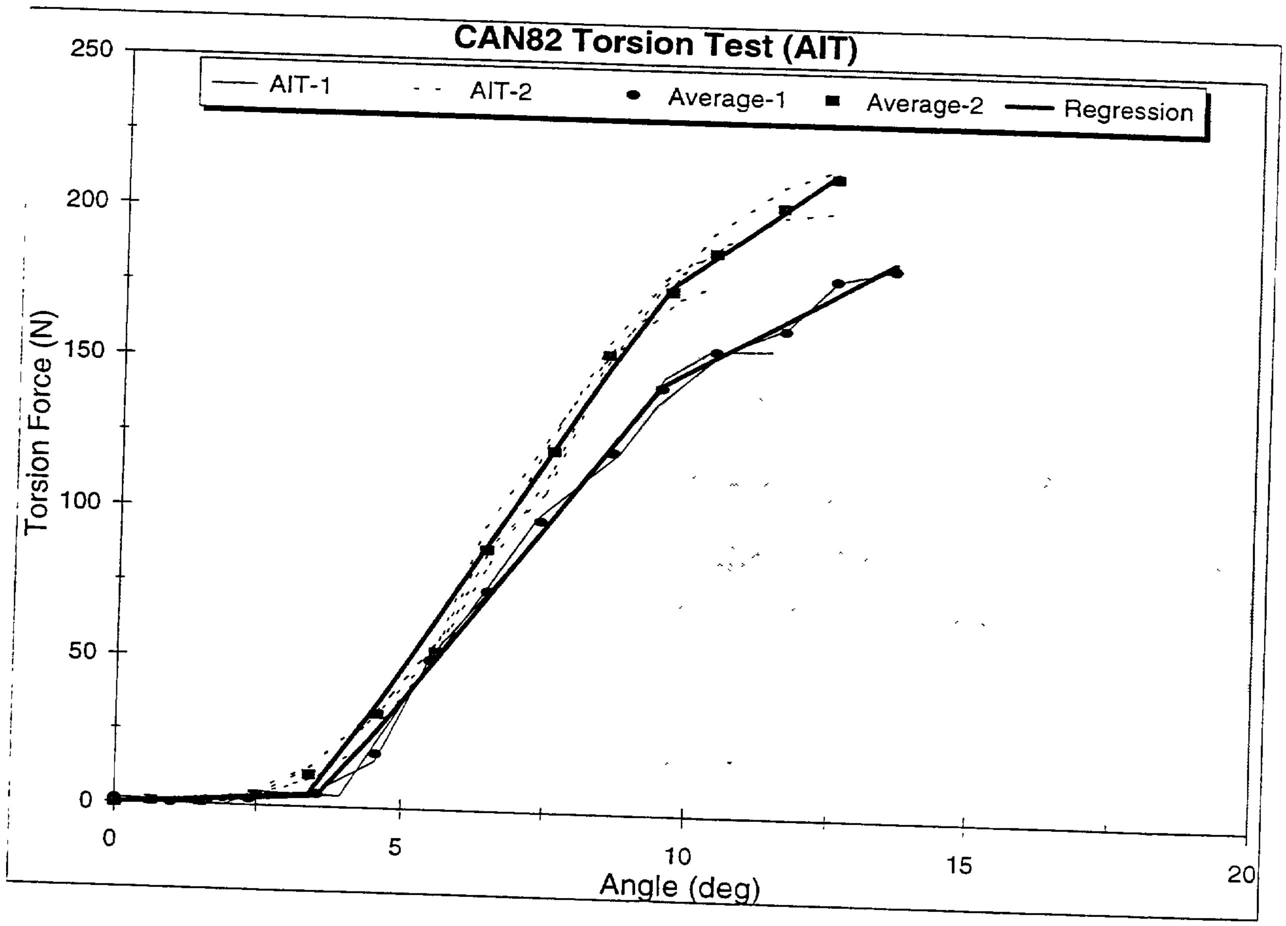


Figure 3.5-1. Torsional moment as a function of angle. Torsional stiffness is defined as the slope of the graph.

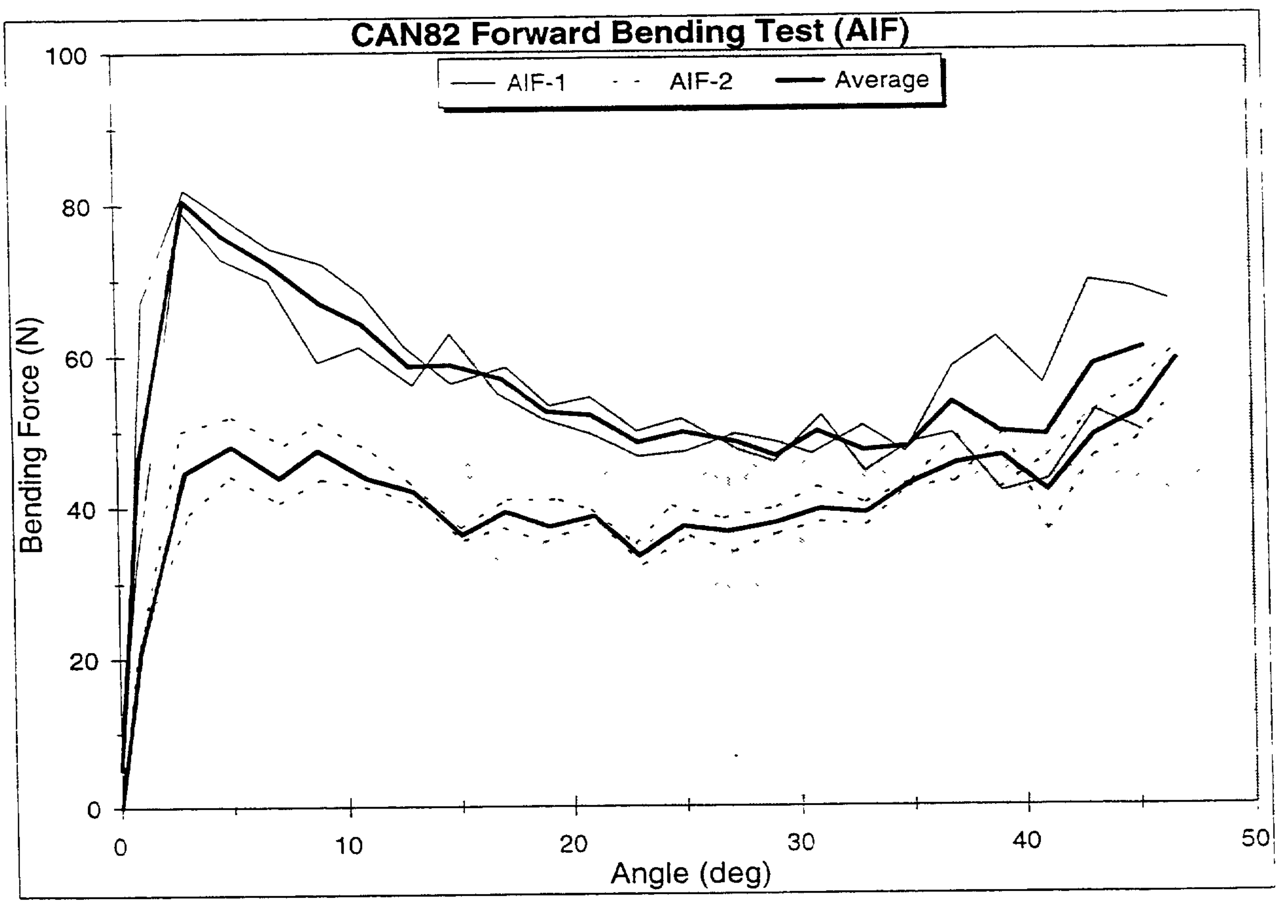


Figure 3.5-2. Forward bending moment as a function of angle. Forward bending stiffness is defined as the slope of the graph.

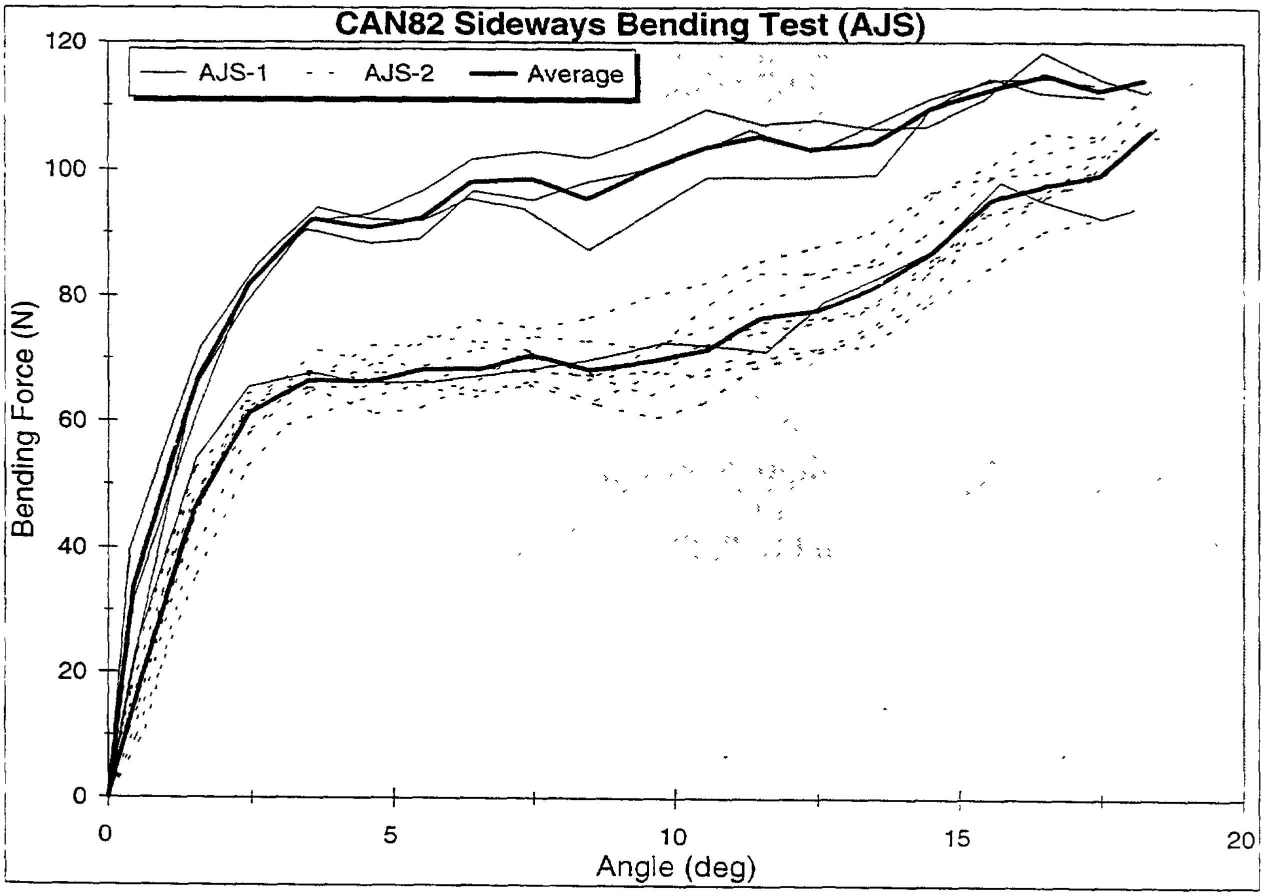


Figure 3.5-3. Lateral bending moment as a function of angle. Lateral bending stiffness is defined as the slope of the graph.

4.0 Discussion

4.1 Displacement Effects

The amount of relative displacement between a load and the user's body that a LCS suspension system allows bears directly on the user's ability to control the load. Optimally, a load will closely follow the motion of the shoulders while allowing the hips to function with minimal resistance. Following the motion of the shoulders is particularly important during motions requiring large displacements (bending over, ducking under obstacles) or rapid changes in direction. A large shift of a heavy load in any direction quickly becomes difficult for a wearer to restrain. This requirement leads to an upper boundary for the acceptable relative displacement of a payload. .

In contrast, low amplitude motions such as walking over level ground, require different suspension system characteristics. With small displacements and accelerations, the human body is able to easily balance slight shifts in the relative position of the load. In overly stiff suspension systems, the relatively small displacements of the body are still closely tracked, resulting in unnecessary forces on the body. All the accelerations and decelerations of the load will be directly transmitted to a users body. These forces, although not large, are cyclically applied and very long duration. As a result, they contribute to local muscle fatigue and higher peak contact pressures. This situation leads to a lower boundary for the allowable relative displacement of a payload. LCS suspension systems that restrain a payload more than is necessary, pay a penalty in user comfort. Based on the earlier Stevenson et al. (1995) contract # W7711-4-7225/01-XSE the initial design threshold limit was suggested to be 12 mm on total motion in the resultant x, y, z directions

For base systems studied, only System C's motion (18.8 mm) exceeded the recommended limit for design in its relative displacement between the person and the payload (12 mm). Three Systems (A,C,D) all are external frames and all had larger "x" displacements values than System B. This would indicate that external frames are more susceptible to larger forward/backward displacements where the pack is not moving with the body. System C had twice the vertical motion of the other systems tested. This would indicate excessive up/down bouncing during walking, a factor which would probably increase the pressure under the straps, increase the tendancy to bump or chaff the user, and cost the soldier more extra energy.

4.2 Moments and Forces Effects

There are several factors limiting that human body's ability to carry a load. These are: muscle fatigue caused by static muscle contraction; transverse shear through the spine; local contact pressure resulting in the compression of nerves; point pressures on underlying structures; and high continuous contact pressures causing compression of underlying tissue, with an inability to oxygenate the tissue. All these factors are effected by the load transfer from the suspension system of the pack to the body.

The stiffness elements within a LCS should serve to transmit the vertical load through the skeleton and onto the spinal column. Any transverse shear load on the spine that is induced by the design, although necessary for equilibrium, is not directed to lifting the weight and can quickly become the limiting factor in load carriage ability. Typically the shoulder girdle and the pelvis are used as the main load transfer areas. The average magnitude of the hip reaction force is a direct indicator of the muscle force required by an individual to support this load and LCS. The amplitude of the reaction forces reflect the ability of a LCS suspension system to attenuate the dynamic loading. High amplitudes require additional muscle forces for load control and a LCS demonstrating high reaction force amplitudes will typically be more energy costly to wear.

System C requires the highest moments to counterbalance the load. Based on Table 3.2-1 it is necessary for the soldier to use greater muscular effort to counter balance the moments of the CWNF pack in comparison to other systems. This would lead to back fatigue and loss of mobility.

Reaction forces were similar across systems. However, when normalized to payload, ANF had the largest forward (x) force and the smallest vertical (y) force. This could lead to better mobility, but also back discomfort due to the effort required to counter balance forward forces (Table 3.2-2).

Based on Table 3.2-3, System C had the largest mean and normalized mean reaction moment amplitude values of all four packs, indicative of the fact that this was a relatively stiff suspension sustem, transmitting large dynamic forces to the body. The large forward-backward moment (My) will result in large counter balancing forces needed at the hips.

System B had the highest amplitude and normalized amplitude for joint reaction forces (See Table 3.2-4) especially in the forward/backward (Fx) direction and upward/downward (Fz) direction. This was also reflected in the normalized amplitude especially for the Fz. The high Fz forces were probably a result of a higher center of gravity of System B. It is primarily a shoulder carry only with a non-weight bearing waist belt. This configuration has been shown lead to improved load control and balance (Stevenson et al., 1995).

4.3 Contact Pressure Effects

As yet, no consensus exists regarding an acceptable safe limit for average skin contact pressures at the shoulder, lower back or hip. From the literature it has been shown that cutaneous blood flow can be reduced by 30% at 4 kPa (Holloway et al., 1975) and can drop to 0% blood flow under 10 kPa (Sangeorzan et al., 1989) or 16 kPa (Holloway et al., 1975). These data served as the basis for recommending a maximum value of 14 kPa for exposures which exceed 8 hours in order to prevent skin necrosis due to blood occlusion. From Stevenson et al. (1995) it was found that average contact pressures at the shoulder which exceed 20 kPa will lead to discomfort in the neck and shoulder region in 95% of soldiers. This value was recommended as a threshold limit value for typical load carriage applications. The sensitivity of skin to instantaneous peak pressures varies widely with the nature of the pressure waveform and the region of the body under consideration. Daniel et al. (1985) reported that high pressures (up to 120 kPa) could be tolerated for several hours without necessarily causing tissue damage. A value of 120 kPa is considered as a threshold limit value for peak pressures in the region of the shoulder, hip and waist until further data are gathered.

4.3.1 Front and Top of Shoulder

The pressure sensor was oriented so that pressures on the front of and top of the shoulder underlying the shoulder strap could be evaluated (See Figure 2.1-2). When results were compared to recommended design guidelines all systems exceeded the average recommended pressure of 14 kPa with no system exceeding the peak pressures of 120kPa based on the Stevenson et al., (1995) Report. The BNF system exceeded all other systems in terms average pressure and peak pressure at 31.2 kPa and 92.7 kPa respectively. This was probably a result of the system being totally shoulder supported with no effective waist belt. DWNF also had higher peak pressure (88.5 kPa), probably as a result of an overlying buckle. Since both BNF and DWNF had two to three times the body forces, their designs obviously place greater stresses on the front and top of the shoulders. Occlusion of blood flow will occur in all base systems tested and this will result in muscular fatigue and higher discomfort ratings.

4.3.2 Back of Shoulder and Upper Back

The average pressures exceeded the recommended design guideline with little variation in magnitudes. The peak pressure under the left scapula for the ANF system was highest as a result of a strap connection in the suspension system. (The F-Scan system is able to detect localized pressure points which may otherwise have gone undetected). BNF and DWNF had a better pressure distribution index (PDI) which would indicate a smoother application of force under the shoulder strap but the same two systems had the highest body force application across the back of the shoulder. When comparing these results to the front of the scapula, Systems B and D had their peak values near the top of the shoulder suggesting that the total shoulder load was larger for these systems. This would suggest that system B and D would be more prone to excessive shoulder fatigue that system A.

4.3.3 Lower Back and Lumbar Spine

System A and C did not rest on the upper lumbar area. Their contact occured in the lower lumbar spine and sacrum areas. System C had the largest PDI ratio but moderate peak pressure with a small contact area resulting in almost no body force against the lumbar spine. Systems B and D, both exceeded guidelines, and had higher body forces than the other systems. . The concentration of pressures in the lumbar area for Systems B and D suggests that the soldier would be prone to fatigue and discomfort at this location.

4.3.4 Lower Lumbar Spine and Sacrum

CWNF had an average pressure and body force almost six times greater than its counter parts. This indicates that the CWNF would cause a muscular fatigue or pressure point problems in the lower back around the sacral lumbar junction and is likely to cause discomfort. The weight of evidence from soldier comments would confirm this finding. Unfortunately, further research is needed to determine the threshold limit value most appropriate for body forces in this area. Although the shear forces in the lumbar spine should not exceed 1000N, these data were not calculated.

4.4 Stiffness Effects

The resistance that a LCS offers to motion is related to the human effort required to force that LCS into the required geometry. A tradeoff occurs between the small amplitude motions of gait and the large motions required for manoeuvrability. In large magnitude motions, high bending and torsional stiffness work against the user. The user must assume awkward or less stable postures to achieve the range of motion required, thus decreasing their ability to control their load. For small amplitude motions like gait, the stiffness of a LCS may allow it to transfer load effectively to the skeleton and if the range of motion required for gait is not restricted, it will perform well during walking. Therefore, for optimal load control, the combined design elements that provide stiffness to a LCS should constrain the load without constraining a user.

5.0 Conclusions and Recommendations

5.1 Specific Conclusions

Table 5.1 provides a summary of the specific findings for the base systems tested using the LC Measurement system.. Each of these findings is also described in the following subsections.

5.1.1 Relative Displacements

1. In terms of relative displacements between the pack and the person, external frames had more motion in the forward/backward direction than internal frames. This would probably result in a feeling of poorer load control.

2. System C had twice the up/down motion of other base systems tested and exceeded the design limit recommended by Stevenson et al. (1995) contract # W7711-4-7225/01-XSE.

5.1.2. Reaction Moments and Forces

3. System C requires greater muscular effort to counterbalance the load moments than other base systems. This muscular effort would likely lead to back fatigue and a loss of mobility.

4. All reaction forces were similar across systems, however, when normalized to payload, System A had the largest forward (x) force required and smallest vertical (y) component which could lead to better mobility but perhaps back discomfort due to the need to counter balance forward shear forces.

5. System C had the largest amplitudes for mean and normalized mean reaction moments. In this design, the relative motion of the payload is high , yet the shoulder straps are quit stiff. This combination results in higher dynamic loading on the wearer.

6. System B had particularly high amplitude and normalized amplitude for joint reaction forces, especially in the forward/backward (Fx) direction and upward/downrd (Fz) direction, a result of the higher center of gravity of the BNF system and a stiff suspension system.

5.1.3 Contact Pressures and Forces

7. Top and Front of Shoulder. All systems exceeded the average pressure recommended in the design guidelines of 14 kPa and exceeded the threshold limit of 20 kPa. These values are expected to result in significant discomfort in 95% of users. Although all systems were under the maximum recommended value for peak pressure, 120kPa, System B and System D had notably high pressure points and body forces.

8. Back of Shoulder and Upper Back. All systems exceeded the average pressure recommended in the design guidelines of 14 kPa. System C exceeded the threshold limit of 20 kPa and can be expected to cause significant discomfort in 95% of users. The peak pressure on the left scapula was highest for System A and was due to a point load created by the shoulder strap.

9. Total Shoulder. Peak pressure values were found near the top of the shoulder for Systems B and D indicating that the total shoulder loads were larger for these systems. This would suggest that Systems B and D would be more prone to excessive shoulder fatigue.

5.1.4 Waist Belt Contact Pressures and Forces

10. Upper Lumbar Spine. Both Systems B and D exceeded the 14 kPa maximum recommended contact pressure and had higher body forces than the other systems. The concentration of pressures in the lumbar area for Systems B and D suggests that the these systems may cause tissue damage when worn for extended periods.

11. Lower Lumbar Spine and Sacrum. System B and C exceeded the 14 kPa maximum recommended average contact pressure. System C also created a very high body force, a value six times greater than its counterparts and exceeding the 135 N horizontal lumbar shear value previously determined. Packs exerting more that this value were rated as causing significant lower back discomfort. (Stevenson et. al. 1995).

12. Total Waist Belt/Lumbar Area. No base system was within recommended pressure guidelines when upper and lower readings were combined. Shorter systems merely placed the pressure higher on the back. System C had body force values that were six times those of other systems.

Table 5.1 Comparative Summary of Major Findings.

Variables	System A	System B	System C	System D
Relative Displacement			Suspension allows 18.8 mm total motion in x and y directions	
Reaction Moments			Total = 56.4 Nm Muscular effort needed in all directions	
Reaction Forces	Need muscular effort to counter forward forces			
Amplitudes of Reaction Moments			Suspension allows twice as much motion as other systems	
Amplitude of Reaction Forces		Higher CofG requires greater x and z forces		
Pressure on Top/Front Shoulder		Highest average and peak pressures and 3 to 4 time higher body forces.		High peak pressure point and 2-3 time higher body forces.
Pressure on Upper Back and Shoulder	Peak pressure point due to shoulder strap design.			
Total Shoulder Pressure Load	Exceeds design guidelines	Exceeds design guidelines and more prone to muscular fatigue	Exceeds design guidelines	Exceeds design guidelines and more prone to muscular fatigue
Pressure on Lumbar Back		Average pressure 3 times other systems		Average pressure 4 times other systems
Pressure on Sacrum			Average pressure 2 times and body forces 6 times other systems	
Total Waist Belt Pressure Load	Exceeds design guidelines	Exceeds design guidelines	Exceeds design guidelines	Exceeds design guidelines

5.2 General Conclusions

The following general conclusions are made about each system.

1. No current load carriage system is capable of transferring forces to the shoulders without excessive contact pressures, under typical load carriage conditions. This was also reflected in high discomfort scores in extended march tests reported in Section C.

2. System A had high peak reaction forces at hip level which could lead to discomfort in the lower back. There was a peak pressure point in the upper back due to a design characteristic of the suspension system.

3. System B had higher hip reaction forces resulting from a higher centre of mass. Standardized tests did not reveal remarkable suspension or load transfer characteristics. The system clearly favored shoulder loading which was reflected in high contact pressures on the top of the shoulder and low lumbar and sacral pressures.

4. System C is unacceptable as a practical military load carriage system. Excessive pack-torso motion and high reaction moments and amplitudes result in poor overall ratings for balance and mobility. The body force on the lower back was excessive at 154 N. This was also reflected in high discomfort scores in extended march tests reported in Section C.

5. System D, as tested, was a working prototype. The suspension and load transfer characteristics observed in standardized tests indicated a stiff suspension with poor pressure distribution at the shoulders, which was typical of System B as well.

6.0 Effect of the Fragmentation Vest

6.1 Introduction

One concern in the military is survivability during operational missions. This is the reason for wearing a personal fragmentation vest, a vest-type garment made up of a inner layered material (Kevlar™) covered by a dense outer shell. This vest is typically a tight fitting garment worn over a t-shirt or combat shirt but under webbing and the rucksack. Military doctrine requires that soldiers wear this protective fragmentation vest (frag vest) under all conditions. Because of the added heat stress, weight, and compatibility problems between the webbing, frag vest, and rucksack, frag vests are often carried either on the rucksack or by military transport. The objective of this study was to evaluate, both on the LC Measurement System and in FAST Trials, the penalty cost of wearing the fragmentation vest as part of standing orders. The purpose of this section is to describe the results from LC Simulator testing with and without the fragmentation vest under the webbing and rucksack system.

6.2 Methodology

For this analysis, systems C and D were evaluated with and without frag vests. The LC Simulator, with a 50^{th} percentile male mannikin, was used for all testing. All test marching orders were loaded with 25kg in the pack and approximately 15kg in the webbing. The protocol described in Section A was followed with data collected after 10, 300, 600, 900, and 1200 seconds of dynamic testing. The same outcome variables were collected, namely : relative motion between the pack and the person, skin contact pressures, and reaction forces and moments of force. For system C, stiffness measures were also taken. For a more detailed description of the LC Simulator methodology see Section A and Annex A.1 of this report.

6.3 LC Simulator: Relative Displacement

Table 6.3-1 is a summary of the relativedisplacement between the pack and the person for Systems C and D. System C without the fragmentation vest had the greatest range of motion of all packs tested. The frag vest served to attenuate the large displacements, especially in the forward/backward (x direction) when it was worn under this system. The relative displacement decreased from 13.6 mm to 5.4 mm with the addition of the frag vest, while the side to side (y direction) displacement was reduced to one quarter of its previous displacement. Similar reductions in relative displacement were not with System D, where relative motion in the forward/backward direction was increased with the addition of the frag vest, while motion in the other directions remained the same.

Table 6.3-1. Relative motion of pack - Frag Effect.

Displacement (mm)	CWNF	CWF	DWNF	DWF
x	13.6	5.4	4.2	7.9
y	6.3	1.8	3	1.9
z	11.4	10.4	9.1	9.9
Total	18.8	11.9	10.5	12.8

6.4 LC Simulator: Reaction Moments and Forces

6.4.1 Reaction Moments

Table 6.4-1 represents the mean reaction moments and normalized mean reaction values. These moments are an estimate of the total counter moment needed by the muscles to accomplish the walking condition when carrying a load. Normalization of mean reaction moments allows for a comparison across packs under different payload conditions. Results showed that reaction moments were reduced about all three axes for system C when wearing the fragmentation vest. The largest decrease was seen in the x moment (Mx), where side to side motion requirements were reduced from 20.2 Nm to 13.1 Nm with the addition of the fragmentation vest. A reduction in Mx was also evident in system D when the frag vest was added.

Table 6.4-1 Mean and normalized mean reaction moments - Frag Effect.

Mean Reaction Moments (N.m)	**CWNF**	**CWF**	**DWNF**	**DWF**
Mx	-20.2	-13.1	-15.1	11.1
My	-52.1	-47	-41.4	-41.8
Mz	-7.4	5.8	3.4	4.7
Total	**56.4**	**49.1**	**44.2**	**43.5**
Normalized Mean Reaction Moments (N.m/kg)				
Mx	-0.03	-0.19	-0.05	0.08
My	-0.03	-0.24	-0.32	-0.3
Mz	-0.03	0.11	0.11	0.03
Total	**0.05**	**0.33**	**0.34**	**0.31**

6.4.2 Reaction Forces

Table 6.4-2 provides data on the mean and normalized mean reaction forces at the hip. Both Systems C and D required larger forward forces (x direction) when wearing a frag vest. This seems to be offset somewhat by a smaller vertical component. The larger Fx value would indicate that the person must use more muscular force to balance the additional weight.

Table 6.4-2. Mean and normalized mean reaction forces - Frag Effect.

Mean Reaction Forces (N)	**CWNF**	**CWF**	**DWNF**	**DWF**
Fx	249	268.4	297	324.4
Fy	37	44.2	42	36
Fz	574.8	563.8	608.3	571.4
Total	**627.5**	**626**	**678.2**	**658**
Normalized Mean Reaction Forces (N/kg)				
Fx	5.8	8.8	9.4	9.4
Fy	-1.3	-1.2	-1.2	-1.3
Fz	8.9	9	8.9	9
Total	**10.7**	**12.6**	**13**	**13.1**

6.5 LC Simulator: Amplitude of Reaction Moments and Forces

6.5.1 Amplitude of Reaction Moments

Table 6.5-1 provides an indication of the extent of oscillation amplitude during frag vest testing, indicating the amount of dynamic counter balancing moment that must be provided by muscles at the hip during walking. Greater values would indicate a need for greater muscular contraction, and therefore effort and subsequent fatigue, during marching activities. For System CWF, the amplitude of the reaction moments was reduced in all three orientations, indicating that the frag vest contributed to damping the motions of the pack relative to the person. This was particularly noticeable in the side to side moments (Mx) and the forward/back moments (My). The reaction moment amplitude did not seem to be affected greatly in System D by the addition of the frag vest.

Table 6.5-1. Amplitude of mean and normalized reaction moments - Frag Effect.

Mean Reaction Moments (N.m)	CWNF	CWF	DWNF	DWF
Mx	40.3	26.2	30.2	22.2
My	104.2	94	82.9	83.5
Mz	14.7	11.6	6.9	9.4
Total	**112.7**	**98.3**	**88.5**	**86.9**
Normalized Mean Reaction Moments (N.m/kg)				
Mx	0.06	0.03	0.04	-0.03
My	0.8	0.4	0.2	0.2
Mz	0.06	0.1	0.04	0.08
Total	**0.8**	**0.4**	**0.2**	**0.2**

6.5.2 Amplitudes of Reaction Forces

Table 6.5-2 represents the amplitude of mean and normalized reaction forces. For both Systems C and D there was an increase in the total force amplitudes in both the Fx and Fz directions when wearing the frag vest. This is particularly true for System C where normalized mean amplitude value increased three fold, indicating a greater need for forward/backward force generation by the muscles to maintain balance. No obvious impact was evident in System D.

Table 6.5-2. Amplitude of mean and normalized reaction forces - Frag Effect.

Mean Reaction Forces (N)	**CWNF**	**CWF**	**DWNF**	**DWF**
Fx	397.6	428.6	425.4	465.1
Fy	81.4	68.8	53.3	39
Fz	505.7	573.6	535.4	584.6
Total	**648.4**	**719.3**	**685.9**	**748.1**
Normalized Mean Reaction Forces (N/kg)				
Fx	-0.2	3.8	3.8	3.4
Fy	0.1	0.2	-0.1	0.4
Fz	4.5	7.9	6.8	7.1
Total	**4.5**	**8.8**	**7.8**	**7.9**

6.6 LC Simulator : Pressure Measurements

Pressure measurements were made with the F-Scan™ system (Tekscan Incorporated, Boston, Massachussets) with sensors placed in the anatomical landmarks areas outlined in subsection 2.1.7 of this report.

6.6.1 Contact Pressures on the Left Front and Top Shoulder - Frag Effect

For System C both the average and peak pressures were increased for testing with a frag vest (Table 6.6-1). This is also reflected in the body force values, which revealed a three fold increase in the forces experienced by the front and top of the shoulder during frag vest testing. The impact of the frag vest on System D was less obvious. Both systems exceeded the average pressure guidelines of 14kPa.

Table 6.6-1. Contact pressures on left shoulder (front and top) - Frag Effect.

	CWNF	CWF	DWNF	DWF
Average Pressure (kPa)	20.5	30.9	24.2	31.5
Peak Pressure (kPa)	47.4	63.2	88.5	67.4
PDI	2.3	2	3.7	2.1
Body Force (N)	35.7	102.3	115.7	104.3

6.6.2 Contact Pressures on the Left Scapula -Frag Effect

For both Systems C and D with the frag vest average pressure on the upper back was decreased but still exceeded the 14kPa guidelines (Table 6.6-2.). Peak pressures were also halved in System D with the addition of the frag vest. System D had a 19% decrease in average pressure with a corresponding 64% decrease in body force at this site. Regardless of the system, both pressure and body forces on the upper back were more acceptable than on the anterior or top of the shoulder.

Table 6.6-2. Contact pressures on left scapula - Frag Effect.

	CWNF	CWF	DWNF	DWF
Average Pressure (kPa)	24.1	15.3	16.4	13.2
Peak Pressure (kPa)	73.8	69.2	34.7	46.7
PDI	3.1	4.5	3.2	3.5
Body Force (N)	73.9	77.7	99.2	35.2

6.6.3 Contact Pressures on the Lumbar Spine -Frag Effect

Only CWNF complied with the recommended average contact pressure of 14kPa (Stevenson et al., 1995) for the lumbar area (Table 6.6-3.). However, this result is somewhat misleading, as CWNF dramatically exceeds the recommended pressure in the sacral-buttock region in compensation for low lumbar pressures. For System D the frag vest tended to decrease the average and peak contact pressures while resulting in a slight increase in body force. The low PDI when wearing the frag indicated that the pressures were more evenly distributed than in System C.

Table 6.6-3. Contact pressures on the lumbar spine - Frag Effect.

	CWNF	CWF	DWNF	DWF
Average Pressure (kPa)	8.5	33	41.6	16.1
Peak Pressure (kPa)	27.1	103	81.9	29.1
PDI	2.6	3.1	2	1.8
Body Force (N)	4.1	18.8	10.1	19.5

6.6.4 Contact Pressures in the Sacral/ Buttocks Region - Frag Effect

Table 6.6-4 contains the quantitative pressure values for frag vest testing with Systems C and D. The CWNF condition created average and peak pressures that were four times that of the other systems tested. These extreme pressure points in the sacral/buttocks area would cause serious discomfort. The frag vest tended to attenuate all pressure measures for System C, which was not the case for System D. Both systems exceeded the recommended average pressure of 14kPa.

Table 6.6-4. Contact pressures in the sacral/buttocks region - Frag Effect.

	CWNF	CWF	DWNF	DWF
Average Pressure (kPa)	76.6	23.3	22.9	37.9
Peak Pressure (kPa)	235	85.7	50.2	65
PDI	3.1	3.7	2.2	1.7
Body Force (N)	154.8	9.3	28.2	33.7

6.7 Stiffness Testing - Frag Effect

Table 6.6-5 summarizes the effect of the frag vest on the torsional stiffness of LCS C and D. Results are also included for DVNF (System D with LCV) and DVF, (System D with LCV and frag vest). The addition of the frag vest increased the torsional stiffness in all configurations. Increased torsional stiffness would be experienced as a loss of upper body mobility.

Table 6.6-5. Torsional Stiffness - Frag Effect.

	CWNF	CWF	DWNF	DWF	DVNF	DVF
Torsional Stiffness (Nm/degree)	1.0	2.5	1.7	2.7	2.0	2.9

6.8 Discussion

Two systems were investigated on the LC Simulator with and without a frag vest. The responses of each system to this testing were quite different. In terms of pack/person relative motion, the frag vest tended to have several positive effects for System C. The frag vest damped the payload motion relative to the person, reduced the moments generated, and decreased the amplitude of the forces and moments in all directions. However, the frag vest did cause increased pressure on the front and top of the shoulder, and significant increases in pressure and body force in the lower lumbar and sacral areas.

System D showed only modest changes in characterisitics (10% to 33%), with the most dramatic changes occuring in the pack/person relative motion and force in the Fx, or forward/backward direction, and the moments about the x axes (Mx). In terms of body force against the skin, greater force was received in the upper back area in the absence of the fragmentation vest. Some higher peak pressure values were also recorded for DWNF. In general, changes between the frag and no frag conditions for System D were minimal, indicating an inherent compatibility between the frag and no frag conditions for this system.

6.9 Conclusions

In System C, wearing a frag vest reduced the relative motion between the pack and the person, creating a tighter sytem. Wearing a frag vest also reduced the side to side moments, a result of cushioning and less relative displacement. The amplitude of the reaction forces and moments were also damped for System C by the frag vest, while little impact was seen for System D when the frag vest was added.

The magnitude of contact pressure in the shoulder region was not decreased when the frag vest was added. The high shoulder forces were accompanied by a large lumbar force (154.8 N), which exceeded the recommended limit of 135 N (Stevenson et al., 1995). Wearing a frag vest helps to reduce this force, but adds stress in the form of heat.

System C with a frag vest had excessively high average pressures on the front and top of the shoulders with sacral body forces and peak sacral pressures of 154.8 N and 235.0 kPa respectively. This level of pressure will cause skin irritation and blisters. System D showed little to no change between frag and no frag conditions indicating an equal level of compatibility.

7.0 Effects of Anthropometrics on Load Carriage Systems

7.1 Introduction

Body size is an important factor on fitting the load carriage system to the individual. Sound ergonomic principles would suggest that the equipment should be designed to fit the average person and be adjustable for other wearers. However, to meet the needs of the fifth percentile female and the ninety-fifth percentile male with the same piece of equipment is an arduous task which has not been accomplished in the civilian pack manufacturing industry. Typically civilian manufacturers have created small, medium, and large packs to accommodate extensive human size differences. However, as these accommodations are made, one cannot be guaranteed that the tissue response characteristics will be the same across different body sizes, especially if the load remains constant. Therefore, the objective of this study was to evaluate two load carriage systems on three (3) mannikins of different anthropometric sizes, namely the fifth (5th) percentile female, fiftieth (50th) percentile male, and ninety-fifth (95th) percentile male.

7.2 Methodology

System B and System C with no fragmentation vest (BNF, CWNF), were compared across the three mannikin sizes. Both systems were tested with a nominal 35 kg load, split between the webbing (10 kg) and rucksack (25 kg). The test protocol followed was the same for marching orders as previously collected in the base systems and frag vest studies. Output variables were also the same and findings are presented more from the descriptive stand point in comparison to other systems and within knowledge of results from the base systems.

7.3 Results

7.3.1 LC Simulator - Relative Displacement Measurements

For System B, total displacement increased with the size of the mannikin such that for the 95th percentile male, total displacement was slightly above the recommended relative displacement limit of 12 mm. However, the method by which total displacements occurred was quite different between smaller and larger bodies. For the 5th percentile female, System B showed greater relative motion in the up and down (z) direction compared to the 95th percentile male where motion in the forward-back (x) direction was greater. For the smaller body size, System B hung from the shoulder and bounced accordingly, whereas for a larger male there is an increase in off-plane motions. For the CWNF System, forward-backward motion and total pack to person motion with the 50th percentile male exceeded the recommended relative displacement limits. There was a tendency to see a decrease in total displacement in System C with increased body size, thus indicating that System C had suspension characteristics which favoured larger body types. There was great difficulty in fitting the System C onto the 5th percentile female mannikin as the frame was a fixed size and exceeded the back length.

Table 7.3 - 1 Relative Motion of Payload - Anthropometric Effects

Displacement		**BNF**			**CWNF**	
(mm)	**5% Female**	**50% Male**	**95% Male**	**5% Female**	**50% Male**	**95% Male**
x	1.9	2.7	9.7	6.4	13.6	3.7
y	1.6	3.2	2.3	2.0	6.3	1.9
z	10.4	11.1	7.5	7.5	11.4	7.1
Total	**10.7**	**11.8**	**12.5**	**11.3**	**18.8**	**8.3**

7.3.2 LC Simulator - Pressure Measurements

Contact Pressure on the Left Front & Top Shoulder - Anthropometric Effects

On the 50th percentile male, both System B and C exceeded the 20 kPa of average pressure recommended as a tolerance limit. Body forces were quite high for both the 5th percentile female and 50th percentile male which, when combined with the back of the shoulder strap, exceeded the recommended body force guideline of 135 N. This extent of body force was evident with the 95th percentile male. Perhaps as the body size increased, the average pressure decreased since the force could be spread over a greater surface area. For the CWNF system, the 5th percentile female experienced greater peak pressures, higher ratio of PDI, and greater body force than the other body sizes. Once again, when the front, top and back of the shoulder strap were combined the body force values exceeded the recommended limits for the 5th percentile female.

Table 7.3-2a. Contact Pressure on Left Shoulder, Front and Top -Anthropometric Effects

Pressure Measures	BNF 5% Female	BNF 50% Male	BNF 95% Male	CWMF 5% Female	CWMF 50% Male	CWMF 95% Male
Average (kPa)	18.2	31.2	14.5	19	20.5	18.7
Peak (kPa)	44.8	92.7	56.4	93.1	47.4	62.7
PDI (kPa)	2.5	3.0	3.9	4.9	2.3	3.4
Body Force (N)	91	132	32.8	64.4	35.7	48.2

Contact Pressure on Left Scapula - Anthropometric Effects

Systems B, on the 5th percentile female, and System C on the 50th percentile male had average pressures exceeding 20 kPa. Although peak pressure on the back of the shoulder did not exceed the recommended limit of 120 N on any body size, when combined with the front of the shoulder, this load limit was exceeded for the 5th percentile female in both Systems B and C, and for the 50th percentile male for System B. With System B, peak pressure points moved lower and closer to the centre of the back with an increase in body size.

Table 7.3-2b. Contact Pressure on Left Scapula -Anthropometric Effects.

Pressure Measures		**BNF**			**CWMF**	
	5% Female	**50% Male**	**95% Male**	**5% Female**	**50% Male**	**95% Male**
Average (kPa)	22.3	17.8	12.3	17.4	24.1	11
Peak (kPa)	59.9	44.9	21.6	59.9	7.38	15.2
PDI (kPa)	2.7	2.5	1.8	3.4	3.1	1.4
Body Force (N)	102.6	81.9	16	102.5	73.9	25.7

Contact Pressures at Lumbar Spine - Anthropometric Effects

Pressure values were measured in the lumbar area where the upper part of the waist belt is situated. For System B, the average pressure for the 50th percentile male exceeded the recommended limit of 20 kPa. For CWNF, the average pressure, peak pressures and a PDI ratio were all excessive at 26.1 kPa, 103.0 kPa and 3.9 respectively, the 5th percentile female. Because System C is a long external frame, there was little pressure against the lumbar area for the 50th and 95th percentile male mannikins.

Table 7.3-2c. Contact Pressure at Lower Lumbar / Top of Sacrum -Anthropometric Effects

Pressure Measures	BNF 5% Female	BNF 50% Male	BNF 95% Male	CWNF 5% Female	CWNF 50% Male	CWNF 95% Male
Average (kPa)	11.2	34.9	10	26.1	8.5	2.9
Peak (kPa)	36.4	81.9	21.9	103.0	22.1	9.2
PDI (kPa)	3.3	2.3	2.2	3.9	2.6	3.2
Body Force (N)	4.5	42.2	9.7	69.4	4.1	0.2

Contact Pressure at Sacrum/Buttocks - Anthropometric Effects

The average pressure exceeded 20 kPa in the area of the sacrum and buttocks for the 50th percentile malefor System B and for the 95th percentile male for System C. There was an extreme peak pressure on the 95th percentile male for the BNF system perhaps due to the loaded rucksack pressing against the skin. This resulted in a high PDI value of 7.7 for System B. There was an extremely high body force in the 50th percentile male of 154.8 N for CWNF, in excess of the recommended body force limit of 135 N. The location of the bottom of the frame and valise contributed to the magnitude of this body force.

Table 7.3-2d. Contact Pressure at Sacrum / Buttocks -Anthropometric Effects.

Pressure Measures	BNF 5% Female	BNF 50% Male	BNF 95% Male	CWMF 5% Female	CWMF 50% Male	CWMF 95% Male
Average (kPa)	14.3	30.2	19.5	17.2	6.6	26.1
Peak (kPa)	43.1	50.2	151.0	69.0	23.5	77.6
PDI (kPa)	3.0	1.7	7.7	4.0	3.1	3.0
Body Force (N)	20.7	24.5	25.9	65.2	154.8	63.4

7.4 Discussion

Based on the data taken across the three mannikin sizes on System B and C, it was evident that body size and shape directly affect the nature and magnitude of the LC Sim output variables. No analyses were performed on human FAST trials to validate anthropometric findings. However, FAST trial subjects reported muscular fatigue, especially at the shoulder region, for both Systems B and C. The higher peak and average pressures experienced by the 5th percentile female and 50th percentile male would suggest that these System designs favoured larger body types. The high concentration of pressure and force in the lumbar area would also suggest that these designs would be excessively tiring for average and smaller bodies.

The implications of findings based on anthropometric size for displacement and pressures measures would suggest smaller individuals bearing the same load would have to contend with greater discomfort. As a future study it would be valuable to assess the impact of different payload masses on humans of differing anthropometrics (in both LC Sim and human field trials) to determine an acceptable level of performance which does not sacrifice comfort.

7.5 Conclusions

Based on a study of two systems across three mannikin sizes, in our opinion, the following conclusions can be made:

1. LC Simulator measurements are sensitive to differences in pack type and body size;
2. Both Systems B and C produce large pressures and body forces in the shoulder areas;
3. In most cases, both Systems B and C produce higher average or peak pressures in the 5th percentile female and 50th percentile male, than the 95th percentile male, thus indicating that these designs favoured larger body types;
4. Both Systems B and C had peak pressure points exceeding the recommended peak pressure limit at different locations dependent on the size and shape of the mannikin and the system tested.

7.6 Reservations

The main reservation is that only two Systems were tested across three mannikin sizes. Because anthropometrically sized and weighted mannikins are available to represent the 5th and 50th percentile females and 50th and 95th percentile males, it would be possible to examine more systems and at more weights thus gaining an understanding of the relationship between body size, load mass and pack type.

8.0 References

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Analysis of LC Systems
Using the Comprehensive Load Carriage Measurement System

Annex B.1

Examples of Test Results for one system

Relative Pack-torso Displacement over Ten Seconds.
Reaction Forces over Ten Seconds.
Reaction Moment over Ten Seconds.
Strap Forces over Ten Seconds.

File: at1b1.dat Test id: Level Walking 1.8 hz, +/-25.4 mm

Summary of Strap Forces

	Shoulder Strap (N)				Waist Strap (N)			
Time (s)	Avg	Std	Max	Min	Avg	Std	Max	Min
0	57	7	65	42	36	5	41	31
300	56	7	66	41	36	5	41	30
600	56	7	66	41	35	5	41	30
900	56	9	65	41	33	7	38	27
1200	56	7	66	41	33	5	39	28
Trial	56	7	66	41	34	6	40	29

Summary of Reaction Forces

	Fx (N)		Fy (N)		Fz (N)	
Time (s)	Avg	Std	Avg	Std	Avg	Std
0	208	23	6	18	942	238
300	206	24	6	19	942	237
600	206	24	6	20	944	235
900	207	24	6	21	946	236
1200	207	24	7	22	948	234
Trial	207	24	6	20	944	236

Summary of Reaction Moments

	Mx (Nm)		My (Nm)		Mz (Nm)	
Time (s)	Avg	Std	Avg	Std	Avg	Std
0	-3	9	-2	31	0	6
300	-4	10	-2	31	0	6
600	-4	10	-1	30	0	6
900	-4	11	-2	31	0	8
1200	-4	11	-2	30	0	6
Trial	-4	10	-2	31	0	6

File: at1b1.dat Test id: Level Walking 1.8 hz, +/-25.4 mm

Range of Reaction Forces

Time (s)	Fx (N) Avg Min	Fx (N) Avg Max	Fy (N) Avg Min	Fy (N) Avg Max	Fz (N) Avg Min	Fz (N) Avg Max
0	168	256	-34	36	429	1269
300	166	258	-34	41	428	1277
600	165	259	-35	40	426	1276
900	167	256	-34	42	442	1275
1200	165	260	-41	44	445	1270
Trial	166	258	-36	41	434	1274

Delta Fx: 92 N
Delta Fy: 76 N
Delta Fz: 840 N

Range of Reaction Moments

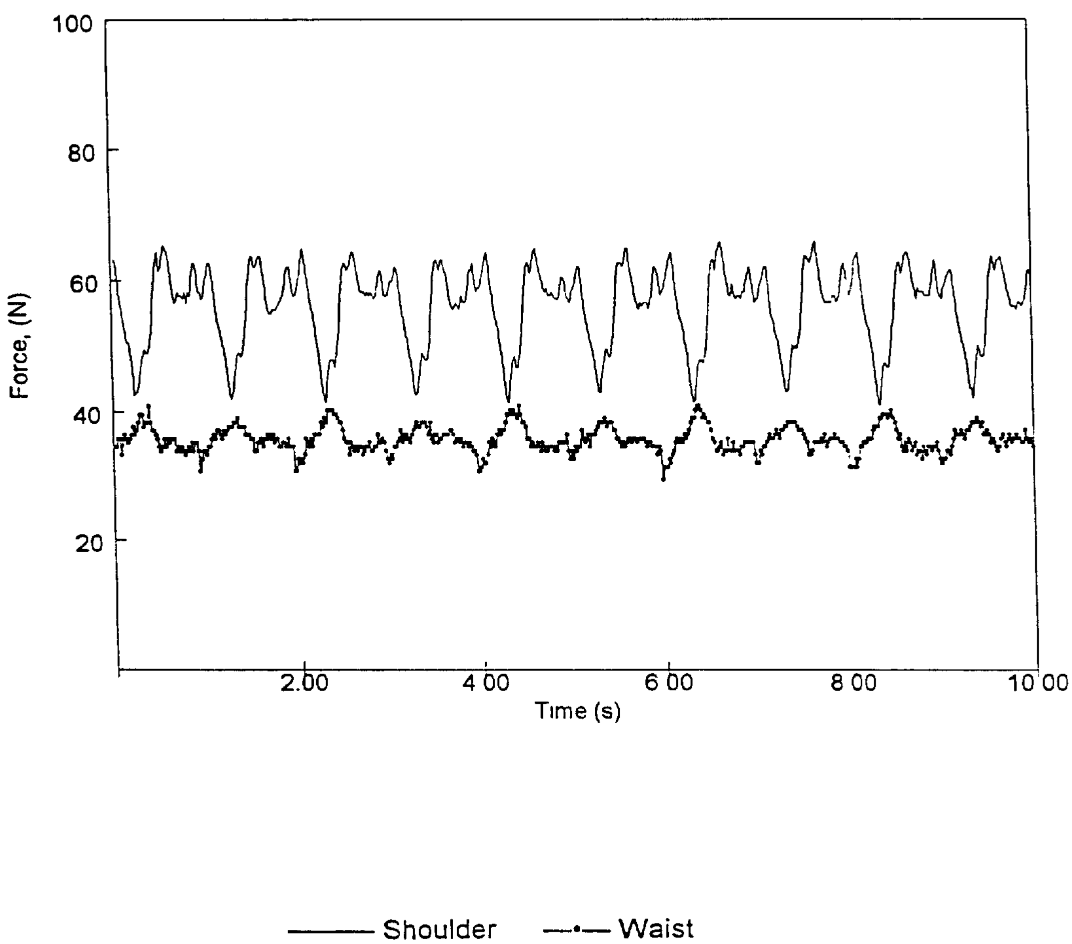
Time (s)	Mx (Nm) Avg Min	Mx (Nm) Avg Max	My (Nm) Avg Min	My (Nm) Avg Max	Mz (Nm) Avg Min	Mz (Nm) Avg Max
0	-15	12	-70	43	-5	5
300	-17	12	-65	46	-5	5
600	-18	13	-64	47	-5	5
900	-18	11	-64	45	-5	5
1200	-20	13	-65	46	-5	6
Trial	-18	12	-66	46	-5	5

Delta Mx: 30 Nm
Delta My: 111 Nm
Delta Mz: 10 Nm

Strap Forces

Level Walk 1.8 hz, +/-25.4 mm

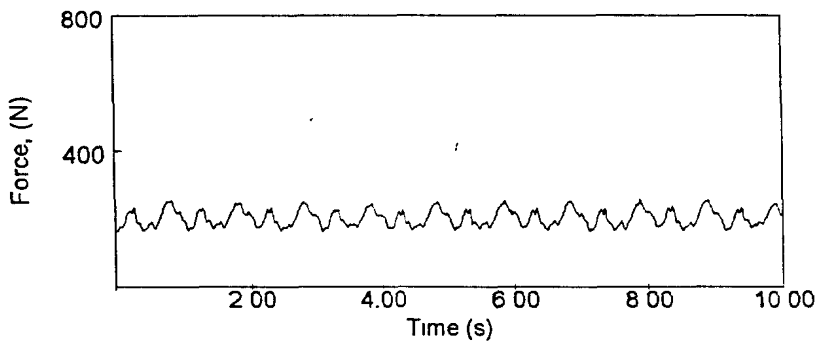
File: at1b1.dat - Time: 300.0 seconds



Reaction Forces

Level Walk 1.8 hz, +/-25.4 mm

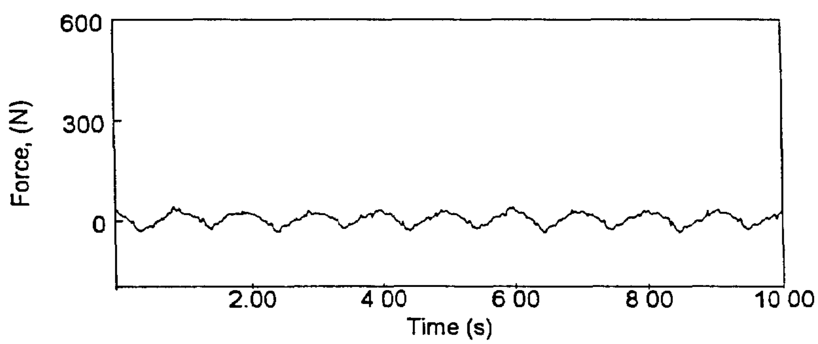
File: at1b1.dat - Time: 300.0 seconds



X Force

anterior/posterior

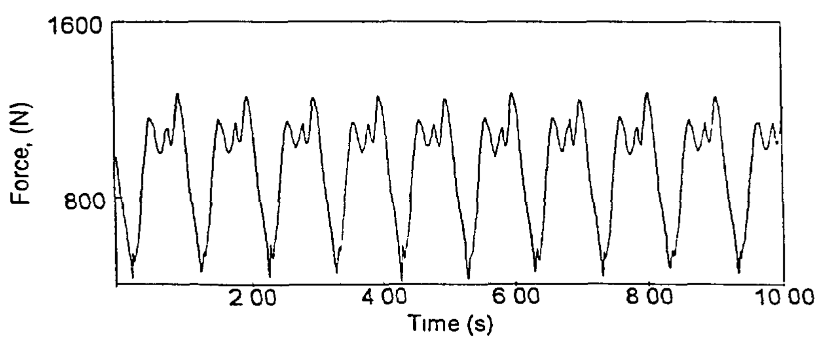
avg min: 166.5 N
avg max: 257.8 N



Y Force

side to side

avg min: -34.3 N
avg max: 40.6 N



Z Force

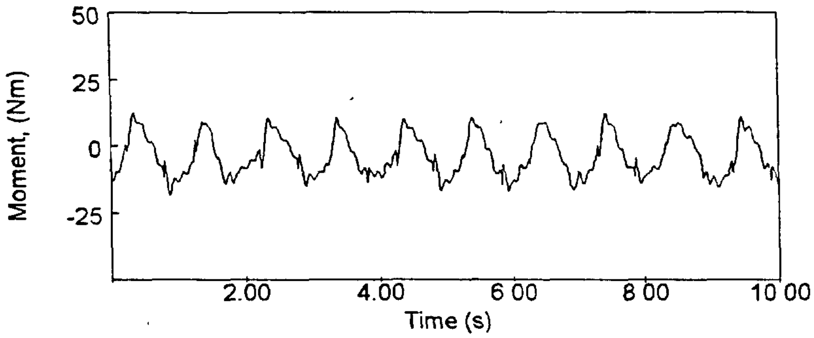
vertical

avg min. 427.7 N
avg max: 1277.2 N

Reaction Moments

Level Walk 1.8 hz, +/-25.4 mm

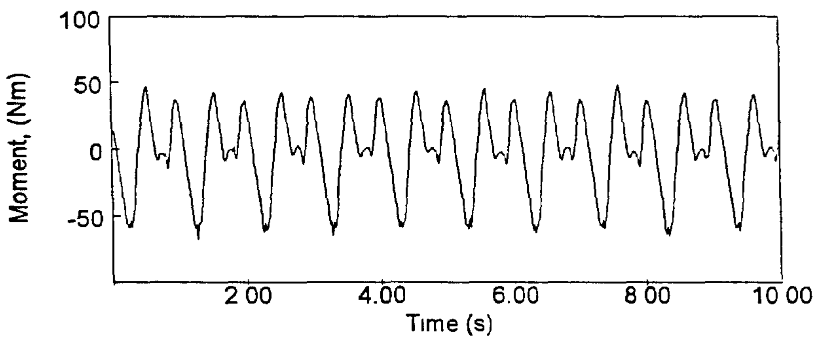
File: at1b1.dat - Time: 300.0 seconds



X Moment

about anterior/posterior axis

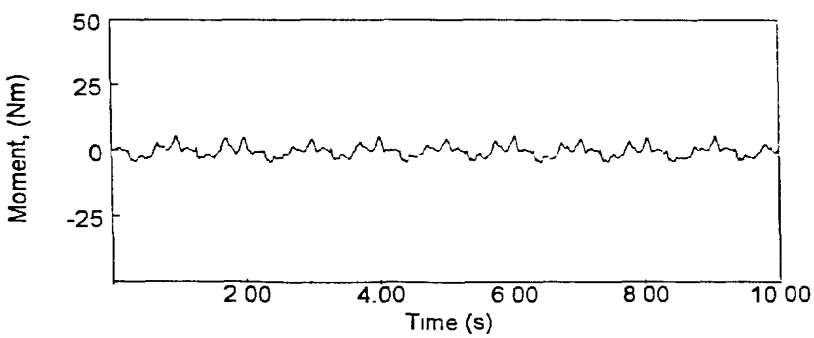
avg min: -17.4 Nm
avg max: 11.6 Nm



Y Moment

about side to side axis

avg min: -64.9 Nm
avg max: 46.3 Nm



Z Moment

about vertical axis

avg min. -4.6 Nm
avg max: 5.3 Nm

DOCUMENT CONTROL DATA SHEET

1a. PERFORMING AGENCY Queen's University, Kingston, Ontario	2. SECURITY CLASSIFICATION UNCLASSIFIED Unlimited distribution -
1b. PUBLISHING AGENCY DCIEM	

3. TITLE (U) Research and Development of an Advanced Personal Load Carriage System Phases II and III Section B: Analysis of Base Systems Using Standardized Measurement Simulators
4. AUTHORS J. Stevenson T. Bryant S. Reid D. Siu

5. DATE OF PUBLICATION October 30 , 1997	6. NO. OF PAGES 86 .

7. DESCRIPTIVE NOTES
8. SPONSORING/MONITORING/CONTRACTING/TASKING AGENCY Sponsoring Agency: Monitoring Agency: Contracting Agency : Tasking Agency:

9. ORIGINATORS DOCUMENT NO. Contract Report 2001-085	10. CONTRACT GRANT AND/OR PROJECT NO. W7711-5-7273/001/TOS	11. OTHER DOCUMENT NOS.

12. DOCUMENT RELEASABILITY Unlimited distribution
13. DOCUMENT ANNOUNCEMENT Unlimited announcement

14. ABSTRACT

(U) The overall objectives of this section of the report were: 1) to conduct standardized assessment of five military systems on a computerized Load Carriage (LC) Simulator using a 50th percentile male manikin; 2) to conduct standardized assessments of three of these systems on a Stiffness Simulator; and 3) to examine the impact of different anthropometric manikins on two base systems. Specifically, the LC Simulator measured variables which assess the load control and load transfer to rotation about three orientations axes. Human responses during First Assessment and Standardized Tests (F.A.S.T.) Trials are reported in Section C and a comparison of these measured dimensions is validated in Section D of this report.

The LC Simulator consisted of interchangeable anthropometrically weighted manikins (50th percentile male used) which were covered with a skin-like surface and driven by computer controlled pneumatic activators programmed to elicit a walking displacement pattern of +/= 25.4 mm amplitude and 1.4 Hz frequency. A trial consisted of loading the pack to 25 kg (=/- 1 kg) payload, measuring system physical dimensions and properties, mounting the pack, and balancing the moments. Five intervals of 10 seconds of data were recorded over a 1200 second period. By this approach, the pack was assessed on the initial setup and after a sustained period of walking. Output variables were: three dimensional displacement of the pack's centre of gravity relative to the bearer; forces and moments from a three dimensional load cell at the level of the hips; and average contact pressures, peak pressures, and skin forces over the anterior and posterior shoulders, and the upper and lower back.

To examine the resistance of the pack frame to load control motions in three planes, a pack stiffness jig was developed. This jig consisted of a Two-piece anatomical human trunk model (50th percentile male) which was designed to limit rotation to one plane at a time. A load cell and a multi-turn precision potentiometer were used to evaluate pack resistance to flexion/extension, torsion, and lateral bending. None of the load carriage systems were capable of transferring forces to the shoulders without excessive contact pressures, under typical load carriage conditions. System A had high peak reaction forces at the hip level which could lead to discomfort in the lower back. There was also a peak pressure point in the upper back due to a design characteristic of the suspension system. System B had higher hip reaction forces resulting from a higher centre of mass. Standardized tests did not reveal superior suspension of load transfer characteristics. The system clearly favoured shoulder loading which was reflected in high contact pressures on the top of the shoulder and low lumbar and sacral pressures. System C was unacceptable as a practical military load carriage system. Excessive pack-torso motion and high reaction moments and amplitudes correlated with poor overall ratings for balance and mobility. The pressure of the lower back for this system was excessive at 154 N. This was also reflected in high discomfort scores in extended march tests reported in Section C. System D, as tested, was a working prototype. The suspension and load transfer characteristics observed in standardized tests indicated a stiff suspension with poor pressure distribution at the shoulders, which was typical of System B as well.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U)

516232

CA011704